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PREDICTION ANALYSIS AND MANAGEMENT DECISIONS

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Summary

The dynamic nature of the Apollo Program, with its many complexities, demands tomorrow's answers today. To meet this need and provide decision bases upon which to act, the Apollo Program Control Directorate of NASA Headquarters has under continuous development rigorous prediction analysis techniques necessary to the detection of potential weaknesses before they become critical. This work is presently pointed toward predictions of space vehicle weight and performance as related to schedules, cost, and reliability. The prediction analysis technique described here combines applicable domains of classical statistical methods, relevancy devices, mathematical modeling, management decision criteria, electronic computer usage, hardware trade-off and error analyses. The techniques developed are not a cure-all, but do provide engineering and program managers that data necessary to pin-point critical issues, define courses of action and thereby factually support technical and management judgements.

Prologue

The Performance Analysis and Control (PAC) group within the NASA Apollo Program Directorate, Washington, D. C. provides technical management support for Apollo launch vehicle, spacecraft, ground support equipment and facilities with respect to: mass properties (includes weight), performance, electrical power, thermal control, vibration requirements, and associated measuring facilities.

The performance analysis and control management system consists of those mechanisms and information flow devices necessary to meet PAC's responsibilities, Table I, with respect to the following objectives:

a. Develop and provide management tools to: review Apollo Space Vehicle development: detect and "flag" areas of potential weakness early in the program before they become critical problems; recommend remedial actions; document status, actions, and evaluations.

b. Assure and support the establishment and implementation of program requirements, standards and guides. Assure and support timely evaluation of program development status against requirements.

c. Develop and provide "quick response" capability to answer requests in, or related to assigned areas.

d. Maintain an active awareness of the needs of other Headquarters offices and Center organizations through effective coordination and information flow.

All of the work conducted by PAC is inter-related within its own assignments as well as to the Configuration Management requirements and needs of other Headquarters and Center organizations.

Prediction Analysis and Management Decisions

Providing, to management, accurate forecasts of potential program weaknesses before they become "critical problems" is a primary Center and Apollo Program Control Directorate responsibility. In discharging this responsibility, the Performance Analysis and Control group (an integral part of Configuration Management) in concert with Marshall Space Flight Center, Huntsville, Alabama, and Manned Space Flight Center, Houston, Texas, is developing rigorous weight/performance forecasting techniques in direct support of the overall management decision making process.

By drawing in depth both on mathematics and on management decision criteria, and by utilizing electronic computers, the developed techniques will allow a manager to single out the critical issues which will require his appraisal and analysis, and will provide him with factual bases to support his executive judgment. In view of the fact that significant portions of these techniques are already available with more to come, this discussion has been prepared to preview and explain the development, utilization and potential of these decision-supporting tools.

The basic objectives of PAT (acronym for Prediction Analysis Techniques) are to assist decision makers in assimilating, analyzing and interpreting large bodies of data for numerous blocks of Space Vehicles so that they can understand the complex inter-relationships between current status, past history, and future status and thereby optimize their decisions.

Prediction Analysis Technique (PAT) Development

The development of PAT has, from the beginning, been planned in considerable detail to eliminate all endeavors and machinations not absolutely necessary to the production and utilization of the desired techniques. This paper will follow the same direction such that the reader will have the most exposure in the shortest time.

The logic behind PAT

The ultimate objective of prediction analysis development effort is to provide a management tool which will continually target and accurately predict the weight and performance of all Apollo Space Vehicles. The final prediction analysis tool will not only embrace weight and performance, but will also include cost, schedule and reliability trade-off effects.

We have chosen to avoid two dangers which inherently creep into discources of this type. The first is the danger of limiting ourselves to an outline of too little depth. The second is the danger of presenting too rigorous a solution or methodology for an area which is truly in development. In essence an effort has been made to follow a middle-of-the-road policy in order to keep our perspective focused on our objectives.

In a broad sense this examination of space vehicle weight and performance can be characterized as being operations research; i.e., research concerned with applying scientific methods to the problems facing executive management.[1] But as pointed out by A. Kaufmann[2] operations research is not, in itself, a science, but rather a scientific attitude towards management phenomena. He goes on to infer, and quite rightly, that there are times when there is little difference of meaning between "econometrics" and "operations research" since the borderlines between the economic and physical areas of technology and management are not clearly defined. Adding to Kaufmann's thoughts; one observes that a revolutionary period in the mathematical and decision logic age is upon us. This new age demands that the technologies of both management and the sciences be welded so as to provide a quantitative prediction of facts upon which final management decisions may be based. In order to assure the success of such decisions, it is of paramount importance to have a formal or probabilistic knowledge of those predictions which are destined to play key roles in the decision process. Therefore predictions, as such, are the heart of the Performance Analysis and Control management system.

It could be opined that predictions as discussed herein are only a hybrid form of statistical analysis. This is hardly worth arguing, since it is through statistical inferences as determined by probability theory that the marriage of mathematics and logic is allowed to occur. Accentuating the word "prediction" draws attention to that area which concerns us most, while recognizing the fact that others have used "trend", and "projection" in a similar vein. Prediction analysis is defined as that process which assesses the facts of yesterday and today, the certainties of tomorrow, and the probabilistic events of the future. In so doing it provides quantitative answers which attest to the existence of a stated condition, (e.g., weight growth) defines its magnitude, and describes the effects of alternate management actions which might be applied is the condition detected detracts from the attainment of stated objectives.

Prediction Analysis Techniques (PAT) to be useful must have the attributes of consistency, efficiency and sufficiency. When applied to the Apollo Space Vehicles, these attributes must be stringently defined because the total number of observations available are limited and will not increase indefinitely as normally assumed in the pure statistical sense. Thus, the following definitions are provided.

1. Consistency is that attribute of PAT which is distinguished by the convergence of the estimated parameter (in this application weight) towards a final value each time an additional set of data is added to the initial set of observations. This means that as our knowledge improves the probability of predicting another value, other than the one upon which we are converging, diminishes rapidly. We choose to refer to this attribute as "targeting".

2. Efficiency is that attribute of PAT which is distinguished by the convergence of the variance of the estimated value (again weight) towards a finite variance each time an additional set of data is added to the initial set of observations. It is further stipulated that said variance be less than or equal to the allowable variance in the final measured weight. This attribute is designated as "accuracy".

3. Sufficiency is that attribute of PAT which is distinguished by the extraction of all possible information from the observed sets of data.

The Beginning of Prediction Analysis Techniques(PAT)

The development of PAT began a short eight months to ensure that Apollo Space Vehicle performance on the launch pad, in flight, and through recovery will be at or near a maximum at all times, and consistent with stated mission and program objectives. Accordingly, the following basic guidelines were established.

(1) PAT must be able to pre-determine far in advance of actual occurrence, changes in weight and preformance which might cause specific mission and/or overall program objectives to be compromised or seriously endangered.

(2) PAT must provide results which allow a program manager to single out the critical issues which require his appraisal and analysis, in addition to providing a factual foundation in direct support of his executive judgment.

(3) PAT must consider all major vehicle interfaces, and attendant design constraints, as related to overall mission objectives.

(4) PAT must be developed to meet the needs of the "on-going" Apollo program, and in such a manner as to insure timely and accurate results. When necessary the concept of "if it works, don't fight it" is to be followed.

Primary and secondary considerations upon which PAT is founded are shown in Table II. These include Apollo Space Vehicle program and mission objectives, ground support considerations, probability of mission success, and a "building block" development plan. End product definition closed the loop and tied all elements of the PAT effort to a common goal. These end products are the working tools necessary to the decision-making process, and are illustrated in Figures 1 through 8. The discussion of end products which follows provides a fundamental understanding of the why's and wherefor's of PAT and its utilization.

A management tool, such as PAT, produces results which can be displayed in many forms. The question arises, how can these results be tailored to the immediate needs of management. Fundamentally, any weight and performance problem which is to be presented must be in concise and understandable form.

This, in itself, is quite difficult to accomplish when you consider that more than twenty Apollo/Saturn missions are planned and that a critical weakness in one vehicle can easily be an inherent part of the others. Also a critical situation could exist not because of a singular major weakness in one area, but because of the cumulative effect of minor weaknesses in several areas.

In what might be called a wide screen view the "How Goes It" bar chart, Figure 1, pinpoints weight/performance trouble spots at the stage and module level, then at the launch vehicle and spacecraft level and finally at the total vehicle level. Such a presentation allows management to focus attention on major problems only. The highlights on this same chart summarize the impact of critical vehicle deficiencies on specific missions and overall program objectives. The "How Goes It" chart is backed by:

(1) A weight/performance deficiency summary, Figure 2, which presents a quantitative deficiency assessment

(2) A trade-off summary, Figure 3, which presents a quantitative assessment of weight/performance, cost, schedule and reliability trade-offs.

(3) A foundation of facts is presented in the weight/performance status summaries, Figures 4 and 5.

(4) Recommended actions with alternate solutions as substantiated by items (1), (2) and (3).

There are three major weight/performance interfaces for the Saturn V Lunar Orbit Rendezvous (LOR) mission. These are:

(1) The Launch Vehicle (LV)-Spacecraft (SC) interface

(2) The Command/Service Module (CSM) - Lunar Excursion Module (LEM) interface

and (3) The LEM ascent - LEM descent interface

Each of these is a PAT end product. In the case of the LV-SC weight/performance interface it is imperative that the launch vehicle payload capability exceed the total spacecraft weight. The ability of PAT to predict tomorrow's problems, thus allowing corrective actions to be taken today, will assure that the LV-SC weight performance interface will not be violated. An illustrative example of the LV-SC weight/performance interface, and the respective trends and prediction lines for both the LV and SC, is presented in Figure 6. The word "trend as used here is defined as the direction in which weight/performance appeares to be going. The definition of "Forecast" is the same as Websters -- an estimate of the future. "Prediction line" is defined as the most probable path weight/performance will follow as concluded from PAT assessments. Even though the LV-SC weight/performance interface may not be violated, mission success is not assured until the other two interfaces are examined. The CSM-LEM weight/performance interface which takes into consideration the ability of the CSM to deliver the LEM to lunar orbit and to eventually return the crew and CM safely to earth is illustrated in Figure 7. Design constraint considerations such as propellant tankage capacities are also a part of these analyses and are reflected in the CSM-LEM interface illustration. The LEM ascent - LEM descent weight/performance interface which takes into consideration the ability of the LEM descent stage to deliver the LEM ascent on the moon, plus the ability of the LEM ascent stage to return the crew safely to the SCM which has been waiting in lunar orbit, is illustrated in Figure 8. Similar design constraint considerations as those made for the CSM-LEM are made for the LEM ascent and LEM descent. In summary, the ability of PAT to predict tomorrow's CSM-LEM and LEM Ascent - LEM descent weight/performance interface problems is just as important as its ability to predict the LV-SC problems.

The Building Block Development Plan

To maintain a proper balance between the ultimate objectives of PAT and an ever present demand for immediate results, the PAT development plan was constructed on the "building block" principle. The "building block" plan is one which provides for tangible results upon completion of each block and contributes directly to the next block until all end objectives are met. The building block plan is illustrated in Figure 9. This approach has paid off handsomely by providing the immediate results required, and has allowed a wide degree of flexibility in the development effort.

Thus far we have seen eight end products and the building-block approach. Involved were the:

(1) "How Goes It" bar chart (mission by mission)

(2) Trade-off Summary

(3) Weight/performance Deficiency Summary

(4,5) Weight/Performance Fact Sheets

(6) Launch Vehicle-Spacecraft Weight/Performance Interface

(7) Command/Service Module (CSM) Lunar Excursion Module (LEM) Weight/Performance-Interface

(8) LEM Ascent--LEM Descent Weight/Performance Interface

The order in which these items appear reflects their relative position in the PAT application hiearchy. For example, predictions of the LEM Ascent and Descent Stages must be accomplished before moving up to the CSM-LEM interface, Figure 7, then on to the next item until the "How Goes It" bar chart is completed. To this list are added,

(9) Stages and/or Modules (except LEM)

(10) Functional Systems (Table III)

Stages include the launch vehicle stages; that is the S-IC, the S-II and the S-IVB in the case of Saturn V and embraces the Adapter and Launch Escape System of the spacecraft. Modules include the command and service modules of the spacecraft. Functional systems include structure, propulsion, electrical power and other systems as illustrated in Table III. The levels at which the prediction analysis techniques are applied are illustrated in Figure 10. Basic PAT application begins at the functional system level. Predictions made here are summed and constitute a stage or module prediction. These are then adjusted by appropriate weight/performance trade-off factors, and when added together provide the applicable launch vehicle capability and spacecraft weight predictions as shown in Figure 6. Basically, what has been outlined is an "inner" building block approach. This is sometimes referred to as a morphological study, i.e., a study of the whole through a study of the elements.

The Nine "Building Blocks" of PAT

Before a block-by-block discussion of the technical aspects of prediction analysis, it is perhaps best to dwell on the factors which are (or are to be) considered by PAT at the functional system level. This additional background will lend support to the rationale of the PAT approach, and should clear up many questions that may have arisen up to this point. For example, what is the basic nature of the input data required for prediction analyses? What are some of its characteristics? What causes it to behave as it does? Since there are a large number of things we do know about the data to be examined, we have tabulated these in Table IV. Clarifying remarks necessary for a better understanding of Table IV follow:

1. Weight and performance information is reported monthly, from which the basic inputs for prediction analysis are extracted. Included are:

    a. Functional System Weights
    b. Engine Performance (Isp, Thrust, etc.)
    c. Real Time (Calendar dates of reported data)
    d. Change Analysis Reports including authorized, pending, planned or proposed changes

2. The change analysis report sets forth those reasons why a weight change has occurred. This report provides the basis for normalizing previously reported data. Normalizing as used herein is analagous to the removal of seasonal effects quite frequently found in econometric data. Monthly change analyses also contribute much to the determination of a true rate of growth by eliminating the effects caused by the transfer of weights between functional systems.

3. Authorized changes are those changes which have gone through a complete engineering approval cycle but have not been officially incorporated via an engineering release. Approximate dates when these changes will become effective are readily established (± one month). Pending changes are those which are in the approval cycle and which appear to be well on their way to becoming authorized. Approximate effective dates can also be established for the pending change within a tolerance of ± two months. Planned changes are those which are being reviewed and

and processed before going through the approval cycle. Approximations of the effective dates of this type change are of a gross nature but can be associated with a probability of occurrence value. The proposed change is one which is subjected to much screening to determine feasibility, impact and actual worth in terms of weight and performance. Its chances of survival are, therefore, very slim unless it meets pre-determined standards. This type of change is not discarded, however, for it becomes a part of a bank (a reserve so to speak) and is subject to recall if changing circumstances warrant it. For example, the rejection of a proposal to change the type of insulation being used in a particular area may have been caused by a heat dissipating source whose later removal makes the original proposal feasible.

4. Measured weights are referred to as actual weights. Weights derived from layouts, sketches and the like are referred to as estimated weights. Weights calculated from officially released detail drawings are referred to as calculated weights. Thus, there are three classes of weight: estimated, calculated, and actual, each with its own inherent error. The class of weight is reported each month along with the applicable functional system to which it applies. In effect, the reported weights have a built-in statistical weighting factor which reflects program maturity.

5. The relationship of the reported data to the program phase schedule (i.e., engineering, manufacturing, test, delivery, etc.) provides a measure of program maturity by allowing for a correlation between the data being reported and the phase it is truly in.

6. Behavioral patterns in certain functional systems can be traced to system interdependence. For example, the electrical power system weight is a direct function of supply and demand. As long as the supply exceeds the demand, an increasing demand will only be reflected by a small weight growth which is readily attributed to wiring. But when the demand exceeds the supply, one can expect a step change in the weight due to addition of batteries or fuel cells. Another example is found in the structural area, where weight changes or changes in design criteria are frequently reflected in structural load changes, and hence sturctural weight. It is also of particular interest to note that the structural weight growth in one stage can be traced to the growth of another via the same structural loads route. This system to system dependence is illustrated in the works of Liebermann, etal, 3, 4.

The Nine "Building Blocks" of PAT

Block #1 - Linear Regression: Immediate results were obtained through the application of linear regression techniques. Specifically, the method of least squares was applied to raw data (weight and calandar time) as extracted from submitted reports. These first results were not satisfactory in that stages with known weight growth problems appeared to be in good shape, while those with no known problems appeared to be growing at abnormal rates.

This was caused by insufficient depth of data, that is, the stage as a whole was analyzed without necessary attention to the individual functional systems which make up the total vehicle. The analytic model in this case was the classic linear model

$$y=a+bx. \tag{1}$$

One shortcoming of the two-variable least squares linear prediction is that it is not accurate beyond the last reported data point. At best, it only resulted in an approximation of the average weight growth which was in existence during one historical period in the lifetime of the vehicle under examination, and gave no real clue to the future. It only said that, if you were to estimate the rate of growth at the last reported point, the average weight growth already detected would be the best estimate, but at that point only. In addition to the two-variable analysis, multiple linear regression techniques were also examined, but with little success. This was primarily due to the fact that a third prime variable was not immediately recognizable.

The effort expended on linear regression analysis did, however, pay off by providing initial results, and further insight into the statistical process, and did point the way for the next two blocks of effort.

Block II - Non-Linear Regression: The Block II non-linear effort embraced the examination of cubic and polynomial equations. The goal here was to introduce a program maturity factor through the variable of time. This work followed a path similar to that charted for linear analysis, but avoided most of the pitfalls which linear analysis uncovered. The results in this instance were not overly significant but did give some indication that the development of non-linear techniques of a type different than the cubic and polynomial might be worthwhile. It should also be noted that this effort was curtailed earlier than planned, to concentrate on the development of the maximum likelihood technique which was beginning to show some promise.

Block III - Maximum Likelihood-Linear: The method of maximum likelihood is an established statistical procedure and was announced by Fisher in 1912.[5] The method of maximum likelihood presupposes that the sample which was most likely to occur has been observed, and that all observations are independent. This latter condition is restrictive in the sense that the random variables, i.e., the observed weights, are assumed to be independent. In a strict sense the observed weights to which we refer are strongly dependent on each other in that each monthly report utilized parts of the data reported in previous months. But in the overall purview of the engineering process it is not difficult to convince one's self that each observation is independent on the basis that the following observation would be made with or without a previous observation and it would be random since design changes are not planned. This means design changes are not planned to occur but are due to a set of random events that do occur during the evolution of the design.

During the adaptation of the maximum likelihood technique to PAT requirements, the effects of estimated, calculated and actual errors were introduced.

The technique which was utilized to accomplish this is described in Reference (6) and is similar to that outlined by Lesourne.[7] Initially the effect of the estimated (E), calculated (C), and actual (A) errors, to which we will henceforth refer to as ECA errors, was insignificant. This situation was due primarily to the large dispersion of initial project weight data. A wide variation in weight data early in a program is not, however, uncommon. With foreknowledge obtained from other programs we do know that the randomness of data decreases as a program progresses and it is on this basis that we visualize the ECA error effect overtaking the random variation and evolving as a primary factor in "targeting" a final predicted weight.

One of the more important features to be found in the maximum likelihood technique is that a prediction line can be extended beyond the last observed data point along with its applicable confidence limits. This is illustrated in Figure 11, and is an ability which was not inherent in the least squares linear regression technique of Block I. One additional innovation introduced at this time involved the normalization of data through a more rigorous examination of change analysis data as it applied to the functional systems. In Block I we only examined weight data at the stage and module level. This resulted in a more sophisticated set of results which were to be further improved under the Block IV effort.

Results of the Block III were formally documented by the issuance of PAC's first Prediction Analysis Memorandum.[8]

<u>Block IV - Maximum Likelihood Non-Linear</u> A limited review of weight data from other space programs resulted in an a priori assumption that as a space program matures there is a tendency for the observed weights to approach the final observed weight asymptotically. Positive evidence of this tendency was visible in Saturn I launch vehicle data and was sufficient enough to warrant the development of an analytic model which would reflect it. An exponential model of the form

$$y=a-be^{-cx} \tag{2}$$

was found to be particularly suited to an asymptotic assumption. Here the values a, b and c are parameters to be estimated, c is restricted to positive values only, and y is a random weight observed at time x.

Earlier comments and assumptions relating to independent variables of the linear maximum likelihood analysis are also applicable to the non-linear case. Similar to the linear model ECA errors are included in the non-linear model and prediction lines are extended beyond the last observed data point. This time, however, confidence limits are not included. Not because they were unwanted, but because the resulting equations were not amenable to a closed-form solution. Although, Monte Carlo techniques could have been utilized to establish such limits, the enormous amounts of computer time which would be required restrained us from doing so. It was decided that confidence limits could be added later if the non-linear model of this Block appeared to be the better prediction device of all those to be examined. Inital applications of the non-linear model were judged to be quite successful on the basis of a non-linear repeating mode analysis program that was also developed during this same time period. Basically, a repeating mode program is one which analyzes a sequential set of observations (five to six points beginning with time zero) and makes predictions for the succeeding months. It then automatically adds the next observed point and makes new predictions for succeeding months. This process is repeated until all available data is exhausted. A plot is then made of these results as a check on the attribute of consistency, i.e., targeting. A typical plot is shown in Figure 12.

One shortcoming of the present exponential model is that it quite frequently converges towards an asymptote which is ficticious. This results when a set of observed data has been growing at a normal rate and then is followed by a period of very little changes, a plateau so to speak. Analysis of data during a plateau period often results in a prediction which is far short of the final weight, expecially if the plateau period occurs early in the engineering development phase. Careful analysis of this type of situation is required if pre-mature asymptotes are to be avoided. Analysis of plateau type data is discussed under Block V. Another limitation of the present model is that it does not allow for independent examination of the various program phases as they are related to weight growth. Program phases are similar to the seasonal changes of econometric analyses. Since early phases normally have a higher growth rate than others, a lack of sufficient observations in following phases could result in an asymptote which is considerably overestimated. As noted by Lesourne[7] this potential danger does not exist in a logistic model of the form

$$y=\frac{a}{1+be^{-cx}} \tag{3}$$

where a, b and c are positive constants. Extreme care must still be used with the logistic model, however, since it too, is subject to the plateau effect previously noted for the non-linear maximum likelihood model. Very little effort has been expended on the development of the logistic model as a prediction tool in view of more promising techniques being developed under Block V effort.

Concurrent with the development of the analytic model preliminary steps were taken to develop computer logic to automatically handle change analysis data. Simultaneously, a computerized data storage and retrieval system was developed to eliminate a tremendous data handling problem. Prior to this, it was necessary to input the data each time a computer run was to be made. With the newer system only the latest observations have to be inserted since previously observed data is already stored. A provision in the analytic program allows the stored data to be retrieved for automatic processing. Automatic data plotting has been used during entire effort. An example of the output is shown in Figure 11. These printouts are enhanced by the manual addition of adhesive type tapes as illustrated. Automatic plotters which can plot graphs with the clarity of the manually taped chart are currently being investigated.

The results of this block of effort were formally documented in PAC's second and third Prediction Analysis Memornadums.[9, 10]

Block V - Math/Logic-Interim Prediction methods of Blocks I through IV assume, a priori, that a specific analytic model will fit the observed data. In the math/logic blocks of effort, the a priori assumption is not applicable, since the analytic model is not pre-supposed but is determined from and is, therefore, dependent on those factors related to the observed data.

In Block V work, which is currently being conducted, strict attention is being paid to known influences which were not readily adaptable to the analytic models of previous efforts. This includes

1. Computerized Change Analyses
2. Targeting and Accuracy Analyses
3. Autoregression Analytic Models
4. Project Time and Real Time Analyses.

The computerized change analyses are sub-routines which evaluate reported changes by the application of go or no-go logic and statistical inference techniques. Briefly, the go or no-go logic program examines individual functional system changes for compatibility with other functional system changes and correlates them with any historical information that has been acquired on a specific change. By the history of a change we mean as it was reported during the proposed, planned, pending and authorized change cycle. The results of the change analysis will:

1. Provide for the normalization of reported data in those instances when weights are being transferred between systems,

2. Validate the randomness of major changes and allows for the removal of what might be referred to as "seasonal" phase fluctuations through the analysis of oscillatory movements and their probability of occurrence during various program phases. Weight changes which are cancelled by the elimination of the requirement which caused them to occur in the first place, are also corrected at this time by proper adjustment of the observed data.

3. Provide the methodology for analyzing proposed, planned, pending and authorized changes. The results of these analyses include the predicted time of effectivity, the predicted magnitude of the change, the probability of occurrence, and the relative error of the prediction.

The targeting and accuracy analyses are sub-routines similar to the repeating mode analyses discussed in the Block IV effort. These analyses provide a continuous check on the convergence of the predicted weight on a final weight, and the convergence of the predicted weight variance towards a final variance.

The autoregression analytic models are currently being developed for prediction analysis, and include stochastic processes such as

1. Markov Chains
2. Random Walk.

Autoregression is defined as a regression analysis process which connects the members of a time series by expressing the predicted value at a point in terms of the values at previous points plus a stochastic term. Stochastic process is defined as a process in which changes of state, related by laws of probability succeed one another at random or determined intervals.[2] In its simplest form the Markov chain is defined as making the result of each observation or prediction dependent on the result of the immediately preceding observation or prediction. For our purposes, the Random Walk is defined as a type of Monte Carlo method which is used to obtain a probabilistic solution by analyzing probable changes in weight (either up or down) to determine the probable weight at specific points in time.

Basically, autoregression technique assumes the variables to be dependent whereas the maximum likelihood techniques forced the assumption of independent variables. We justified our assumption of independent variables on the basis of the obvious existence of random variation between observations. We justify our assumption of dependency on the premise that data normalization as effected by our change analysis sub-routines removes the major random variation effects thus making each new observation directly dependent on the preceding observations.

The utilization of project time rather than real time is directed towards the effecting of a time scale transformation to account for different levels of activity during the lifetime of a project. For example, during the periods of relative inactivity real time would shrink when expressed in terms of project time, and it would expand if design activity were accelerated to meet schedules or other commitments. The transformation of real time to project time will be enhanced by the utilization of PERT output data, and allows projections to be made of future real-time/project time relationships. The project time concept should overcome the "plateau effect" which was noted in the discussion of non-linear maximum-likelihood analyses. In summary, this effort is primarily aimed at developing an autoregression methodology which includes change analysis sub-routines, prediction of weight in terms of both project and real time, plus determining the values of probability which will apply to final predicted weights.

Block VI - Math/Logic-Pre-Dynamic Pre-dynamic is defined as being that period in PAT development before we provide the feed-back loop which assesses the management decisions based on PAT predictions and other Program perturbations. It is during the Block VI effort, however, when the initial provisions will be made for the processing of feed-back data. The major effort in this period will be directed towards finalizing all applicable PAT methodologies which were developed in prior blocks, updating all data storage and retrieval programs, and providing technical reports, computer programs and users guides

Additionally, the cross effects of the growth of one functional system on another will be incorporated, as well as those effects emanating from the inter-dependence existing between stages and modules.

Block VII - Math/Logic-Dynamic Block VII effort will see the incorporation of feed-back loop into the PAT programs. As currently envisioned, the feed-back loop will utilize a sub-routine which assesses the certainties and pro bable events of the future as determined from management decisions which are predicated on PAT prediction results, and other related Apollo Program information.

This effort will be geared to examining resultant effects of said events on weight/performance, individual vehicle mission requirements, schedules, cost, and reliability. A decision relevancy technique will be developed to evaluate each of the aforementioned areas on the basis of both quantitative and subjective material. A priority listing will be established, through a relevancy system (some may call it figure of merit), which quantitatively rates alternate decision paths which could be followed by management. The quantitative ratings will include probability of success values, and an overall priority rating matrixed against cost, reliability, schedule, weight/performance, and mission and program objectives for each decision path being contemplated.

Block VIII - Post Dynamic The PAT methodologies which evolve from all previous efforts will be utilized to evaluate the effects of factors not normally amenable to rigorous numerical analysis. Considerations such as legislative and executive actions, extra-territorial actions, budgetary actions, state-of-the-art advancement in technological areas, logistics and spares, and contract change actions, are to be examinated for their cross-effects on both mission and program objectives.

The larger part of this effort will be concentrated on the establishment of a list of detail items to be considered under each action. This will also include the assignment of probability numbers in addition to probable cost and schedule values.

Block IX - Math/Logic - Prediction Analysis and Management Decisions Simply stated this effort will result in final NASA Prediction Analysis and Management Decision documents.

Conclusions

The ultimate value of the Prediction Analysis Techniques described here, or any technical tool, is truly measured by the usefulness of the results it provides. In the case of our PAT device the usefulness of results can be predicted upon the data shown in Figures 1 to 12. Management can, by fusing these data, e.g., current and predicted launch vehicle weights and capabilities and spacecraft weight; figure of merit for total vehicles and their individual stages and modules; schedule and cost effects and trade-offs; provide itself with alternate paths to reach mission success or problem resolution. To make this job easier a comprehensive work sheet has been devised to help the individual who performs Apollo Space Vehicle program analyses, interpretation, and subsequent decision-making to visualize the complex relationships involved.

The results of the first phase of the Prediction Analysis Technique program have been so favorable that we feel, that for the first time, a real engineering and management tool capable of anticipating and pin-pointing future hardware and associated software status is now available. The weight and performance aspect has been used as a vehicle with sufficient tangible assets to "prove-out" and develop PAT. PAT cannot predict the outcome of a horse-race or what tomorrow will bring on the stock market. But the Apollo Program is amenable to prediction analysis techniques since it has specific end goals, and scheduled for key events.

Though no panacea, PAT has shown itself to be an accurate device in weight and performance predictions. The obvious move into cost predictions in combination with reliability is now underway.

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Table I

PRIMARY RESPONSIBILITIES

1. Weight/Performance
2. Electrical Power
3. Thermal Control
4. Vibration, Shock and Acoustics

ARE MET BY

1. Prediction Analyses
2. Weight/Performance Constraint Analyses
    (a) Structural
    (b) Propulsion
3. Mass Property Error Analyses
4. Mass Measurement Facilities, Requirement and Capability Validation
5. Trade-off Factors (weight/performance, cost schedule, reliability)
6. Information Flow System
7. Instruction Aids
8. NASA/DOD Technical Data Exchange
9. Overall Configuration Management Relationships

Table II - PAT Development Considerations

	Considerations	
Guidelines	Primary	Secondary
(1) PAT must be able to pre-determine far in advance of actual occurrence changes in weight and performance which might cause specific mission and/or overall program objectives to be compromised or seriously endangered.	(a) Program Objectives (b) Flight Mission Objectives (1) Saturn V (2) Saturn IB (c) Program Development Plans	(a) Alternate Mission Assignments (b) In-Flight Experiments
(2) PAT must provide results which allow a program manager to single out the critical issues which require his appraisal analysis in addition to providing to him a factual foundation which directly supports his executive judgment.	(a) Trade-Offs (1) Weight/Performance, (2) Cost, (3) Schedule, (4) Reliability (b) Recommendations with Alternate Courses of Action	(a) Composite Managements Reports on weight/performance Status (b) Hardware developments, Manufacturing and checkout requirements.
(3) PAT must consider all major vehicle interfaces and attendant design constraints, as related to overall mission objectives.	(a) Launch Vehicle vs. Spacecraft (b) Lunar Excursion Module (LEM) vs. Command and Service Module (c) LEM Ascent vs. LEM Descent (d) Mission Profile and Velocity Budgets	(a) Weight/Performance Control Limits (b) Weight/Performance Trade-Offs (c) Functional System Effects (d) Structural Interface Conditions (e) Propulsion Performance & Propellant Capacity
(4) PAT must be developed quickly to meet the needs of the on-going Apollo Program, and in such a manner to insure timely and accurate results	(a) A "Building Block" Development Plan (b) Application of Time Tested (c) Improvement of Available Methods (d) Development of Hybrid Methodology (1) Mathematics and Decision Logic (e) Definitions of PAT Accuracy requirements as Related to (1) Weight/Performance (2) Cost, (3) Schedule, (f) Controlled Data Flow and Qualitative Evaluation	(a) Expert Consultation (b) Adaptability to Changes (Flexibility). (c) PAT Computer Programs (NASA internal use only) (d) PAT Reports, Memoranda and Technical Notes (e) Total Space Vehicle Error Allocation (f) Mass Property Error Budget (1) Inert Weight (2) Propellant loading (g) Measurement Facility Accuracy

Table III

Typical Functional System Breakdown

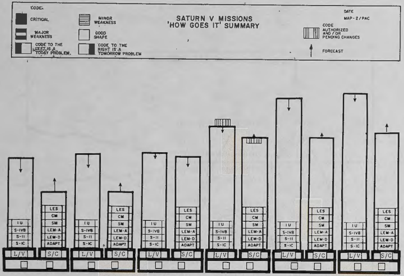
Functional Systems

Structure (stages, interstages, crew compartments, etc.)
Landing & Docking (landing gear, docking structure, flotation systems)
Protection Systems (ablator, acoustic, meteorite, radiation)
Personnel Accomodations (furnishings, seats, food, etc.)
Propulsion (engines, plumbing, pressurization)
Environmental Control (temperature, pressure, fire)
Guidance and Navigation (inertial, stellar, planetary)
Electrical Power (fuel cells, batteries, wiring, etc.)
Instrumentation (sensors, antenna, transmitters, etc.)
Communications (tranceivers, antenna, cameras, etc.)
Personnel (crew, suits, life support equipment, etc.)
Cargo (scientific instruments, experiments)
Propellant Reserves (flight performance, launch window propellant utilization, etc.)
Residual Propellants (pressurants, trapped propellants, bias, etc.)
Propellants (thrust buildup and decay, and full thrust)

Table IV

Things Known About Data To Be Examined

1. Data is formally reported once a month
2. Reported data is a result of
    (a) Actual weight measurement
    (b) Calculations based on detail
    (c) Estimations based on design layouts i.e., also calculated but based on less information than that found on detail drawings
3. Reported data is accompanied by change analyses.
4. Authorized, Pending, Planned and Proposed Weight/Performance change information is submitted monthly.
5. Data is reported on a functional system basis.
6. There are schedules for hardware development (design, manufacture, test, checkout, etc.)
7. There is inter-dependence between functional systems
8. There is inter-dependence between stages and modules
9. Functional system development schedules are different
10. Functional system design criteria are defined in specifications and contractual documentation.
11. Design reviews are held quarterly (approximate) with resultant design changes-reflected in change data.
12. Actual weight data has relatively small error
    Calculated weight data has modest error
    Estimated weight data has high error
13. Data of early phases subject to high random variation (due to refinements in design criteria which were previously approximated; first and second level optmization; tradeoffs between systems; and previously ignored secondary design conditions becoming primary design conditions.
14. Weight accounting is a daily procedure and if a daily porcedure audit were to be made and the results plotted, a waveform pattern would be evident as opposed to month saw tooth trend.
15. The effectivity (i.e., schedule) of authorized, pending and planned changes can be established. Thus providing for knowledge of future happenings.
16. Weight data is dependent on engineering releases. Releases are planned and scheduled. Weight is, therefore, time dependent.
17. Weight data is supplemented by % Actual, % Calculated and % Estimated information.
18. Government furnished equipment is included in weights and is not normally subjected to strict weight control requirements
19. Contractors are contractually obligated to specification weights.
20. Design constraints exist. (e.g., tank capacities, size restrictions, factors of safety, etc.)
21. Month to month reporting frequently reflects step function when plotted (can be attributed to stretchout of schedule, several months of status quo due to major redesign effort, design nearing completion, or changes which are sporadic and far apart.
22. The number and magnitude of weight changes decrease repidly after the design and manufacturing phases.
23. Major changes can occur as a result of testing effort waveform pattern begins to resemble a harmonie.
24. Reported status of estimated, calculated and actual data does not necessarily coincide with reported engineering releases.



HIGHLIGHTS :

FIGURE 1--"HOW GOES IT" BAR CHART

SATURN V SPACE VEHICLE			WEIGHT/PERFORMANCE DEFICIT, EQUIVALENT PAYLOAD, LBS			COST (2) (MILLIONS OF DOLLARS)			RELIABILITY (2) (PROBABILITY OF MISSION SUCCESS)			SCHEDULE IMPACT, MONTHS			PACING ACTION DATE
VEHICLE NO.															
L/V	GSM	LEM	L/V	S/C	TOTAL SPACE VEHICLE	L/V	S/C	TOTAL SPACE VEHICLE	L/V (1)____	S/C (1)____	TOTAL S/V (1)____	L/V	S/C	TOTAL SPACE VEHICLE	

(1) Reference Values
(2) Maximum Values as Related to Weight/Performance Deficit Only

FIGURE 2--TRADE-OFF SUMMARY CHART

SATURN V SPACE VEHICLE			TODAY'S			TOMORROW'S ACTION FORECAST											
VEHICLE NO.						LAUNCH VEHICLE EQUIVALENT PAYLOAD, LBS					SPACECRAFT, EQUIVALENT SPACECRAFT WEIGHT, LBS						
											NAA SPACECRAFT			GRUMMAN LEM			
L/V	CSM	LEM	L/V CAPABILITY	CONTROL LIMIT	S/C WEIGHT	S-IC	S-II	S-IVB	IU	TOTAL L/V	CSM(1)	LES	TOTAL	ASC.	DESC.	TOT-AL	TOTAL S/C

(1) Includes Adapter

FIGURE 3--DEFICIENCY SUMMARY CHART

WEIGHT/PERFORMANCE STATUS

L V No. ______________
CSM No. ______________
LEM No. ______________

DATE: ______________
MAP-2 (PAC)
MISSION TYPE: ______________
MONTHS TO LAUNCH: ______________

FIRST ORDER MISSION OBJECTIVES	REQUIREMENTS	STATUS
(1) (2) (3) (4)	(1) (2) (3)	

LAUNCH VEHICLE					CONTROL LIMITS			SPACECRAFT				
ENGINE ISP		ISP CHANGE IN TERMS OF LBS PAYLOAD	STAGE	WEIGHT TREND LBS PAYLOAD/MO	L/V CAP	LES WT	S/C WT	WEIGHT TREND LBS PAYLOAD MO	STAGE	ISP CHANGE IN TERMS OF LBS PAYLOAD	ENGINE ISP	
REQM'T	STATUS										REQM'T	STATUS
			S-IC S-IC/S-II Interstage S-II S-II/S-IVB Interstage S-IVB IU Total L/V		CURRENT STATUS				CM SM Adapter LEM LES Total S/C			
					L/V CAP	LES WT	S/C WT					
					PRIMARY PROBLEMS							
		+ Nominal								+ Nominal		

HIGHLIGHTS

FIGURE 4--WEIGHT/PERFORMANCE FACT SHEET NO. 1

WEIGHT/PERFORMANCE STATUS

L V No. ______________
CSM No. ______________
LEM No. ______________

DATE: ______________
MAP-2 (PAC)
MISSION TYPE: ______________
MONTHS TO LAUNCH: ______________

LAUNCH VEHICLE TRADE-OFF FACTORS						SPACECRAFT TRADE-OFF FACTORS					
STAGE	LBS/LB PAYLOAD	PERFORMANCE LBS PAYLOAD/PERF	COST $$/LB PAYLOAD	SCHEDULE LBS PAYLOAD/(NO.) MO	RELIABILITY LBS PAYLOAD/% RELIB	STAGE OR MODULE	LBS/LB S/C	PERFORMANCE LBS PAYLOAD/PERF	COST $$/LBS PAYLOAD	SCHEDULE LBS PAYLOAD/(NO.) MO	RELIABILITY LBS PAYLOAD/% RELIB
S-IC Sep. S-IC/S-II Interstage S-II Sep. S-II/S-IVB Interstage S-IVB Sep. IU						CM Gross SM Burnout SM Gross Adapter LEM LES					

LAUNCH VEHICLE/SPACECRAFT FORECAST

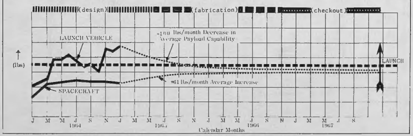


FIGURE 5--WEIGHT/PERFORMANCE FACT SHEET NO. 2

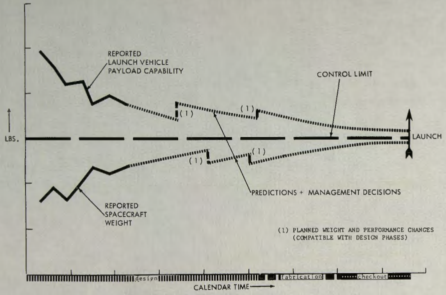


FIGURE 6---THE LAUNCH VEHICLE/SPACECRAFT WEIGHT/PERFORMANCE INTERFACE

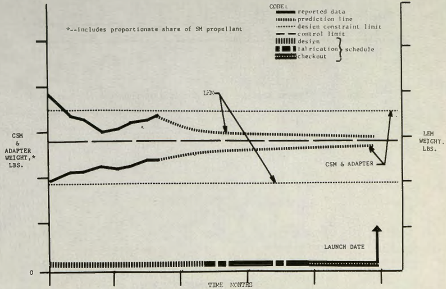


FIGURE 7--THE SPACECRAFT(CSM)/LUNAR EXCURSION MODULE(LEM) WEIGHT/PERFORMANCE INTERFACE

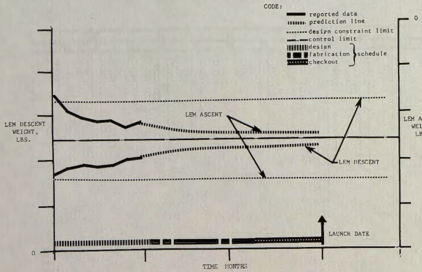


FIGURE 8--THE LEM ASCENT/LEM DESCENT WEIGHT/PERFORMANCE INTERFACE

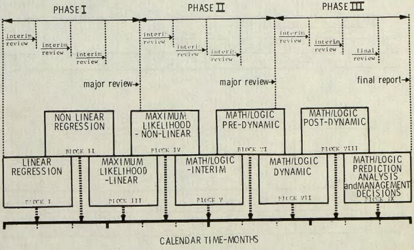


FIGURE 9--"BUILDING BLOCK" DEVELOPMENT PLAN

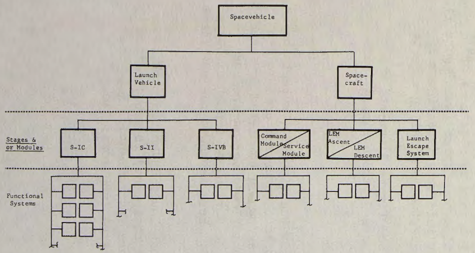


FIGURE 10-- LEVELS OF APPLICATION OF PREDICTION ANALYSIS TECHNIQUES

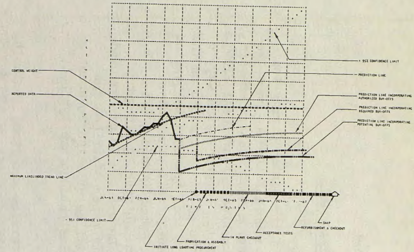


FIGURE 11--TYPICAL PREDICTION CHART (COMPUTER PRINTOUT)

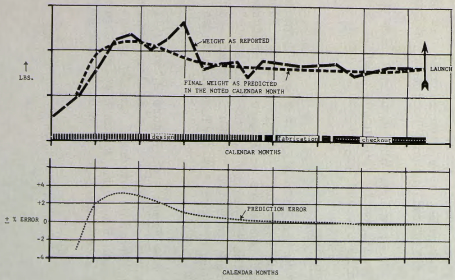


FIGURE 12--PREDICTIONS BY THE REPEATING MODE TECHNIQUE