HANDLE VIA [redacted]
CONTROL SYSTEM

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AERONAUTICAL CHART AND INFORMATION CENTER
SECOND AND ARSENAL, ST LOUIS, MISSOURI 63118

[redacted]

REPLY TO ATTN OF: ACDM

20 May 1966

SUBJECT: Automatic Payload Attitude Determination System

TO: [redacted] (Major Albert W. Johnson)

1. Attached is an analysis prepared by Dr. William C. Mahoney, Hq ACIC, of a proposal submitted by Lockheed Missile and Space Corporation, in response to a verbal request by Major Albert Johnson, [redacted] A preliminary draft of this analysis was left with Major Johnson and DIAMC [redacted] and [redacted] by Dr. Mahoney at meetings on 6 May 1966.

2. The system, called APAD (Automatic Payload Attitude Determination), will provide continuous attitude and attitude rate data during primary camera operation. This information, in conjunction with calibration of the panoramic cameras, will completely define the geometry of the KH-4 system for MC&G exploitation.

3. It is the overall conclusion of the analysis that the claims made in the Proposal are in accord with present "state of the art" and, therefore, capable of being met. It is also generally concluded that APAD:

a. Will enable significant economic and manpower savings to be achieved in preparation of MC&G products by FY 1970.

b. Will provide the means for what amounts to a data reduction "breakthrough" by making possible improvements in analytical data reduction and increased efficiency in automated ground data reduction equipment by FY 1970.

c. Will increase quality and accuracy of mapping at medium scale.

It is strongly recommended that APAD be implemented as soon as possible into the KH-4 camera in conjunction with the implementation of internal calibration of the panoramic camera.

[redacted]

COPY No. [redacted]

PAGE 1 OF 2 PAGES

ATCH - 1

HANDLE VIA [redacted]
CONTROL SYSTEM ONLY

4. In order to allow timely consideration of the attached paper, information copies are being distributed as shown below in accord with discussions with Major Johnson, [redacted] and [redacted]

FOR THE COMMANDER

[redacted]

Technical Director

1 Atch
Analysis

Copies to:

[redacted]

EVALUATION OF THE APAD CONCEPT

FOR INERTIAL ATTITUDE DETERMINATION

20 May 1966

1. Introduction

A presentation for a proposed system of inertial attitude determination was made at a meeting sponsored by [redacted] on 17 March 1966. The concept for this system, called "Automatic Payload Attitude Determination" (APAD), was developed by the Lockheed Corporation in response to stated requirements by users in the intelligence community involved in photographic interpretation, mapping, and targeting activities.

2. Background

As originally conceived, the KH-4 camera system was regarded solely as an intelligence gathering and surveillance system characterized by high resolution, but poor geometry. In spite of its geometric deficiencies, DOD map and chart producing agencies and NPIC demonstrated that materials obtained from this system could be used for mapping and targeting. Later, at the instigation of the users, a 1 1/2 inch focal length terrain frame camera, locked to a sideward looking stellar camera, was added to the system in order to provide the means for removing the most significant geometric distortions and to determine attitude of the prime panoramic cameras of the system. The result of this innovation was to extend the application of the KH-4 system to mapping topographic detail to meet medium and some large scale mapping requirements.

Reduction of panoramic camera materials requires the application of highly sophisticated measurement and data processing techniques. In response to user requirements to reduce mensuration, speed analytical data reduction processes, and improve accuracy of results, further improvements have been programmed for the KH-4 system which are designed to give better control over internal panoramic geometry. They are:

a. Incorporation of a calibrated reseau in the prime panoramic cameras.

b. Redesign of the panoramic cameras to improve dynamic stability.

c. Incorporation of collimated light sources on lens axis which relate motions of rotating lens to reseau calibration marks.

d. Replacement of the present Stellar Index (SI) 1 1/2 inch focal length frame camera with a 3 inch focal length frame camera.

e. Replacement of the present stellar camera with an improved dual stellar camera configuration.

With the addition of a calibrated reseau in the panoramic cameras, a requirement was generated for data on the measuring attitude rate changes of the photographic vehicle. Previously, these effects were hidden in the uncertainties of film distortions. With improvement of panoramic geometry, however, knowledge of attitude, attitude rates, and attitude rate changes become meaningful and must be applied if more efficient, accurate, and economical methods of data acquisition and reduction are to be developed. It is this consideration which is considered paramount in ACIC's analysis of the APAD concept.

3. Description of the APAD Concept

The APAD System senses attitude through the use of two strapped down electrostatic gyros rotating on axes at 90° to each other. Where practical, calibration of the physical characteristics of the gyros which result in measurable biases during operation, is to be done on the ground. Initial attitude and drift of the gyros will be calibrated on-orbit using correlated stellar data or other electronic sensor methods taken during the period of operations.

It is proposed that gyro data be recorded in binary form for three positions on each panoramic exposure and at a higher sampling rate on a magnetic tape which would be carried in the recovery capsule. Magnetic tape recordings can attain a frequency of 50-75 samples/second or about 20-30 samples/panoramic exposure. Maximum potential recording rate of the system is 750 samples/second. Present limitation is imposed by lack of stated recording capacity. Multiple revolution and line averaging techniques are to be used to reduce combined pick-off and quantizing noise.

4. Evaluation of APAD Accuracy Claims

In the Contractor's Proposal, it was estimated that APAD, in conjunction with stellar materials, would be able to provide absolute attitude to a standard error of 3.86 seconds of arc on each axis using one stellar observation per hour based upon a drift rate of 0.0001 degree/hour. It is capable of providing an accuracy of 122 seconds of arc (standard error) with one stellar calibration in 14 days.

The following references were obtained to evaluate claims of the Contractor regarding APAD accuracy:

[redacted]

The document relating to the [redacted] reported an analysis of readout error of ESG taking into account systematic and random errors. This study concluded a readout rms error of 3.3 arc seconds could be attained.

Document [redacted] reported that the latest stability data for an ESG gyro tested under an Air Force Contract, [redacted] were .0001 and .0002 degrees/hour for two and five day runs respectively. In Document [redacted] it was predicted overall gyro performance, including all factors, would improve to .0005 degrees/hour in a 1-G environment, and to .00005 degrees/hour in an orbital environment. Major reasons for improvement on-orbit is attributed to:

a. Stabilized temperatures in vacuum.

b. Reduced gravity field.

c. Reduced field strength requirements.

d. Continuous operation.

These studies also indicated that after initiation, gyros can be speeded up and reach thermal equilibrium in about 10 minutes starting from -65°C, hence, implying that a mission could be flown entirely within stability limits indicated above.

In a meeting held between representatives of [redacted] Lockheed, and [redacted] on 6 May 1966, it was agreed that assuming both pre-launch and on-orbit calibration, APAD could attain the accuracies stated in the Lockheed Proposal.

Limitations on absolute attitude data are related to the quality and number of on-orbit observations, stellar or otherwise, which are used to calibrate ESG for drift and other systematic errors. Attitude rate information is limited by gyro stability. Based upon the above considerations and information, it is concluded that the accuracy claims for ESG made by Lockheed are valid and operationally feasible.

5. Requirements for Attitude Determination for Mapping, Charting and Geodesy (MC&G)

With the availability of calibrated reseau controlled panoramic materials, the following attitude requirements must be met in order to exploit KH-4 materials with maximum accuracy and efficiency:

a. Absolute attitude to within a standard error of 5 seconds of arc for roll, pitch and yaw respectively.

b. Attitude rates and attitude rate changes known to an accuracy compatible with the accuracy of internal calibration of KH-4 prime panoramic cameras.

c. Availability of precise readout of attitude data within one month after receipt of materials for MC&G exploitation.

d. Conversion of attitude and attitude rate data into continuous form as a function of vehicle time for use in data reduction processes.

These requirements are based on present KH-4 mission altitudes of approximately 80 Nautical Miles. In order to exploit the KH-4 system more effectively for medium scale mapping, consideration is now being given to flying the system at higher altitudes, around 200-300 Nautical Miles. Under this condition, absolute attitude determination requirements are more stringent and will exceed those stated above.

a. Absolute Attitude Requirement

In a Memorandum from DIAMC-TA to Chairman of COMOR, MC&G Committee, Subject "Research and Development Requirements for Satellite Image-Forming Acquisition Systems for Mapping, Charting and Geodesy", a requirement is stated to develop attitude sensors to determine attitude within a standard error of five arc seconds on each rotation axis. This requirement is addressed primarily to materials obtained at altitudes less than 100 Nautical Miles.

b. Attitude and Attitude Rate Requirements for the Improved KH-4

The proposed improved KH-4 system, due to be launched in the early part of calendar year 1967, will be dynamically more stable than the present KH-4 system and will have markedly reduced rotation rates due to external and internal disturbances. Based upon studies made by the manufacturers of the prime camera system and vehicle, this system will be subject to three types of dynamic disturbances:

Initial Start Disturbances
Steady State Disturbances
Attitude and Rate Correction Disturbances

(1) Initial Start Disturbances

As the vehicle approaches an area of interest, the rotating drums of both the forward and aft cameras are activated. Due to momentary momentum imbalances, instantaneous roll rates are generated up to 150 degrees/hour. Attitude roll rate detection sensors are then activated which cause attitude correction jets to fire to provide damping. Damping time usually takes about 4-10 seconds covering 2-4 panoramic exposures.

(2) **Steady State Disturbances**

During steady state operation, after all initial start conditions have been damped, the vehicle is subjected to natural drift rates which are modified if the following limiting numerical dead band values are exceeded:

$$\phi_E + 12\dot{\phi}_E > \pm 1/4^\circ$$

$$\omega_E + 12\dot{\omega}_E > \pm 1/4^\circ$$

$$\kappa_E + 12\dot{\kappa}_E > \pm 1/4^\circ$$

where $(\phi_E, \omega_E, \kappa_E)$ Absolute values (degrees) of pitch, roll, and yaw with regard to vehicle coordinate system with respect to center of dead band.

$(\dot{\phi}_E, \dot{\omega}_E, \dot{\kappa}_E)$ Pitch, roll, and yaw rates (degrees/second)

During steady state operation, roll and pitch rates do not exceed 60°/hour and 20°/hour respectively.

IMC correction for the pan cameras is accomplished by tilting the entire camera unit at programmed rates. Depending upon the start-up time and the differences in camera operation, the nodding of the forward and aft cameras may or may not be synchronized. Nodding of the panoramic cameras causes a cyclic perturbation on the basic pitch rate. When both cameras are exposing the terrain at the same time, the cycling perturbation induces pitch rates of 12°/hour during each exposure. Conversely, when both cameras are 180° out of synchronization, perturbations up to 27°/hour can occur. Between these two extremes, variations occur in a discontinuous manner depending upon frequency match of both cameras.

In addition to programmed IMC, programmed crab is also fed into the vehicle to correct for image smear perpendicular to the line of flight.

(3) <u>Attitude and Attitude Rate Correction Disturbances</u>

Attitude and attitude rate correction jets are fired whenever the following occurs:

(a) Vehicle dead band function is exceeded as given in Para (2) above.

(b) Vehicle rates exceed:

Pitch	40°/hour
Roll	60°/hour
Yaw	20°/hour

Correction jets are pulse type, fired one at a time and having the following effects on angular rates:

Pitch	3°/hour/pulse
Roll	14°/hour/pulse
Yaw	3°/hour/pulse

Based upon its aerodynamic characteristics in a drag environment, the vehicle eventually tends to be held against either end of the dead band limit with pulse firings taking place at an average frequency of 1 pulse/ 20-30 seconds around each rotation axis.

It has been proposed that pulse jet firing be recorded as a means to determine attitude rates. Lacking any other information, these recordings will at least indicate when any radical change in rates has occurred. They will not tell what the actual rates were before or after such corrections are applied. Solution for actual rates cannot be obtained unless it is also known why the correction was applied, i.e., dead band or exceeding rate limit.

c. <u>Summary of Vehicle Dynamics</u>

With reference to Para b, it is quite apparent that roll rates will vary quickly through a range of ±150°/hour during the first 4-10 seconds of simultaneous stereo start up for panoramic camera operation. These corrections will not be smoothed, but will be subject to radical discontinuous variations based upon the reaction of the attitude control system to the induced vehicle roll rates.

During steady state operation, the vehicle is affected only by characteristic drift rates and cyclic perturbations due to the nodding camera mechanism which provides for vehicle IMC in line of flight.

Roll rates will not exceed 60°/hour with corrections in each axis at an average frequency of one every 20-30 seconds.

Average pitch rates are subjected to less variation resulting in pitch rate corrections on a more extended frequency. Current quotation estimates based upon vehicle operation furnished by Lockheed Corporation are that the mean period between pitch corrections is probably around 20-30 seconds. Cyclic perturbations occur in the basic pitch rate between 12° and 27°/hour for each panoramic exposure.

Yaw rates are extremely low and corrected at about the same frequency as pitch and roll.

Since operation of the attitude correction jets is independent of camera operations and since both panoramic cameras operate independently of each other, affects of such correction can be initiated at any part of the scan of either cameras. Based upon a 3.125 second minimum [redacted] rate of the stellar camera associated with the KH-4 system, and assuming an average independent correction frequency for roll, pitch and yaw at once every 30 seconds, the probability of having at least one correction between stellar exposures is greater than 1/4. Superimposed on this probability is the continuous cyclic perturbation of 12-27°/hour on pitch rate for IMC compensation. Under steady state conditions, roll and pitch rate changes could reach 60°/hour and 40°/hour respectively. When such rates occur without being detected or compensated for, pointing error within a panoramic photograph will be affected as much as 12 seconds of arc measured from the center of the photograph (equivalent to 36 microns in the photograph image plane). This is nearly three times the rms error tolerated in panoramic camera calibration and two and one-half times the rms accuracy of stellar attitude determination. Since the time interval between a forward and aft exposure could be as great as 2.4 seconds, it is possible that more than one correction could occur at almost the same time which could further magnify pointing error differences between exposures.

These errors are not compatible with total internal calibration accuracy of the panoramic camera and attitude determination accuracy required by DIAMC for KH-4 camera system.

d. Precise Readout Requirements

The materials obtained from the A Program provide the only experience ACIC has had with time delay for readout of precise attitude data. Table I tabulates the date the mission was flown and when precise attitude data, derived from stellar camera materials, was accepted at ACIC.

TABLE I

MISSION	DATE FLOWN	ATTITUDE DATA RECEIVED
9046	10/62	10/65
9058	9/63	10/65
9059	10/63	3/66
9065	6/64	2/66
9066	8/64	2/66

Clearly, the precise reduction of stellar data is subject to considerable delay. As a consequence, considerable effort was expended at ACIC to meet interim ACIC production commitments.

Reduction of KH-4 stellar data is currently being performed at a much lower accuracy. Until the time of incorporation of the panoramic reseau, a requirement for precise reduction of KH-4 data did not exist except in areas not covered by materials from the A Program. With the availability of calibrated panoramic materials, this will no longer be the case, since attitude for each panoramic exposure must be known precisely if maximum savings are to be realized in exploitation of controlled panoramic materials for MC&G.

Each of the above A missions contained about 4,000 stellar exposures. Each improved KH-4 mission will provide a maximum of about 15,000 stellar frames/mission leading to a yearly volume increase of about 15 times over that provided by A. If past experience is any guide, it is quite obvious that a precise stellar reduction is going to saturate production capability and fail to meet the one-month requirement. Introduction of APAD will eliminate this problem by reducing the amount of measurements to be performed by at least 2 orders of magnitude.

APAD is also required to satisfy preliminary intelligence needs for readout of all stellar data within a standard error of 3 minutes of arc in pitch, roll and yaw within one week. The current KH-4 system, containing about 400 stellar exposures, is usually processed within 96 hours. If only three times as many are reduced (1,200 instead of the full 15,000) the one-week limit will still be exceeded.

Of course, in both the above cases, procedures could be modified to limit the amount of data to be reduced. The price paid is lack of flexibility and response to exploit KH-4 materials to meet intelligence and other user requirements which is the prime purpose for flying the missions in the first place.

e. Attitude and Attitude Rate Conversion for Production Use

It is required for the precise data reduction process that attitude rates be determined as a function of time. If data is provided at comparatively long intervals, then it is required that it be examined for discontinuities to determine when attitude accelerations have occurred. This process can be time-consuming and become more subject to personal judgement as the interval between observations is increased. To be compatible with panoramic calibration and camera capability, it is necessary that the rate of data acquisition be as high as possible - at least four times within one panoramic scan during steady state conditions and at least fifteen times per scan during attitude correction periods to reduce errors of angular measurement below an rms of five arc seconds.

6. Data Reduction of Improved Calibration KH-4 System

In the present proposed method of data reduction to be used at ACIC, the 3 inch focal length camera will act as a geometric control to determine any radical distortions on the panoramic geometry caused by vehicle dynamics.

To minimize the effects of such dynamics and to take into account the long period angular rate conditions, maximum use will be made of the stellar camera to determine what these angular rates are. Since the cycling period of the stellar camera is 3.125 seconds during panoramic camera operation, it is estimated that this camera system will be able to detect any long trend attitude or attitude rate changes, but will not be able to detect those that occur within the cycling frequency of the stellar camera. In order that such unknown changes will not affect the exploitation process, a larger number of points must be measured which can be empirically related to the frame camera. This process of data reduction will insure that data reduction accuracies meet DIA standards for map accuracy and target position determination.

In normal production using improved KH-4 materials, it is estimated about 1,000 manhours will be required to generate control data to support a medium scale compilation. After FY 68, ACIC is scheduled to produce about 200 such compilations each year. With complete continuous attitude data, point measurement time per compilation can be reduced by about 50% resulting in about 100,000 manhour savings a year. An additional maximum of 40,000 manhours per year can eventually be saved through simplification in stereoplotting instrument operations based upon a time savings of 200 hours for each of the planned 200 medium scale compilations.

Assuming an average ACIC document manyear rate of [redacted] year, the total estimated savings that could accrue from point mensuration and compilation would amount to about [redacted] year.

In addition to cost savings, calendar time and manhour savings are also becoming critically important to ACIC due to increased automation of compilation equipments. It is absolutely essential that mensuration activities be speeded up if production imbalances are to be avoided.

The estimated standard errors for attitude determination for the improved KH-4 stellar camera attitude sensing systems are 10, 10, and 20 arc seconds for roll, yaw, and pitch respectively. This corresponds to a standard pointing error greater than 60 microns at the scale of the panoramic photography and 8 microns for the 3 inch focal length frame camera.

The improved KH-4 panoramic cameras are to be calibrated to within a standard pointing error of 15 microns which corresponds to about 2 microns at frame camera scale. This level of frame pointing absolute accuracy is at present unattainable. If attitude, along with calibration, is known to within 5 arc seconds, panoramic pointing accuracy will be at least equal and probably better than that predicted for the frame camera. In this event, there will no longer be any requirement for the 3 inch camera as control for panoramic geometry, but only to satisfy small scale mapping needs at scales 1:500,000 and smaller, certain other types of photogrammetric triangulation and special targeting activities. If orbit altitudes are increased from 100 to 300 Nautical Miles, the requirement for a frame camera will diminish even more due to loss of ground resolution.

7. Application of APAD to MC&G Data Reduction

Since APAD will provide continuous, accurate attitude rate data, then, along with the calibrated panoramic reseau, uncertainties of geometry which currently affect panoramic materials can be eliminated, resulting in more accurate and better quality MC&G products. These improvements are a direct consequence of greater mensuration precision, resulting from more favorable scales and elimination of complicated adjustment procedures that must now be employed in compilation processes to compensate for present uncertainties. As a further consequence, larger compilation and mensuration error margins can be tolerated, allowing for a reduction in manpower expenditure and use of less critically trained personnel.

The inclusion of panoramic reseau and APAD to the KH-4 system will provide the means for achieving what amounts to a data reduction breakthrough in processing photo materials obtained from this system. This will be achieved through simplification of attitude determination procedures and establishing a basis and justification for more efficient operation and development of MC&G Automated Ground Data Reduction Equipment.

Simplification of attitude determination will result from computerization and reduced stellar mensuration. Based upon the requirement of only one, or at most, two stellar reductions per pass, only a fraction of total stellar reduction will be required as to what would be needed without APAD. Note, too, that sufficient data would be available to more completely exploit panoramic geometry as opposed to only marginal capability using stellar materials alone.

Knowledge of rates and attitude readouts will have tremendous impacts on data reduction implementation. By knowing absolute attitude and attitude rates completely, as well as having calibrated reseaus, maximum exploitation can be realized from the automatic map compilation equipments being developed in DOD. By eliminating absolute orientation and empirical adjustment of models prior to stereo compilations, the efficiency of automated instruments such as the AS-11B/C and UNIMACE, can be increased significantly by FY 70.

Under present scheduling arrangements, the new 3 inch camera will fly sometime around 1 January 1967. It is proposed that a new stellar camera to meet the 5 arc second requirement will be made available sometime in July 1968. The APAD Proposal states that a strap down ESG could be ready by the time the new stellar camera is ready. Subsequent discussion has also revealed that other techniques can be proposed which can eliminate requirements for a stellar camera altogether and allow direct on-orbit calibration for ESG drift biases. For this reason, decisions regarding APAD at this time would be timely in order to avoid unnecessary development costs for a new stellar camera. ok?

APAD would also apply to [redacted] and [redacted] systems. It is especially desirable on [redacted] to support the 3 inch frame camera being flown for MC&G to meet small and limited medium scale compilation requirements. ?

8. Cost Effectiveness and Savings

It has been estimated by the Contractor that the following savings could be effected using APAD:

ITEM	SAVINGS/MISSION
Increased Coverage (Deletion of Horizon Cameras)	[redacted]
Stellar Data Reduction	[redacted]
TOTAL	[redacted]

In addition to the above savings, the Contractor added another [redacted] by stating the stellar/terrain camera could be eliminated if APAD were substituted. Since this camera has important application in efficient production of small scale mapping materials, it is questioned whether this elimination is desired and hence, not included in the above.

In Paragraph 6, it was estimated APAD controlled calibrated reseau materials could result in a maximum yearly savings of [redacted] at ACIC based upon a yearly production of 200 medium scale map compilations per year. Assuming an equivalent additional savings throughout DOD and a yearly rate of 10 missions per year, it is estimated an average MC&G savings would amount to approximately [redacted] per mission. Adding to the above, gives a total savings of [redacted] per mission. The cost of APAD was estimated by the Contractor as follows:

Development, AGE, Tracking & Software	[redacted]
Procurement and Acceptance Tests of 20 Systems	[redacted]
Total Cost of 20 Systems	[redacted]
Average Cost/System	[redacted]
Total Cost for Each System After First 20 Systems	[redacted]

[redacted]

Based on the above, it appears that APAD cost savings over the first 20 missions could be as high as [redacted] To this might be added additional savings if the system were applied to other satellite systems not considered in this paper and possible savings in automating ground data reduction equipments given the growth potential offered by APAD type data inputs.

9. Conclusions

Based upon the information furnished on the APAD system accuracy, cost and savings, data and DIA MC&G requirements, and analysis of impact effects on ACIC operations, it is concluded that:

a. APAD is feasible and within range of the technology of present "state of the art".

b. APAD will provide increased attitude and attitude rate determination accuracy over present stellar methods to meet DIA Stated Requirements to COMOR.

c. Improved quality of attitude data, in conjunction with panoramic calibration improvements, will permit production of more accurate and better quality map and target products.

d. APAD will provide precise attitude data to meet DIA requirements significantly faster and in less manhours than present stellar reduction methods. ?

e. APAD will allow complete exploitation of calibrated panoramic materials without dependency on the accompanying frame camera and without the uncertainties which will exist because of the inability of stellar observations to detect cyclic perturbations occurring between observations.

f. APAD will significantly reduce the data reduction effort presently associated with improved KH-4 materials through reduced mensuration and simplified compilation procedures.

g. APAD, through its adaptability to computer processing, will allow improved exploitation and further development of automated ground data reduction equipments associated with MC&G activities.

h. APAD will allow significant savings of manpower and dollars in MC&G production of Maps, Charts, and Target Materials.

10. Recommendations

It is recommended that:

a. The APAD concept be incorporated into all future KH-4 systems.

b. Further studies should be made to verify its usefulness in other systems.

Prepared By:

William C Mahoney

DR. WILLIAM C. MAHONEY
Supervisory Physical Scientist