CONTROL AND GUIDANCE RESEARCH AT NASA

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ABSTRACT

A program of advanced control and guidance research is under way within the National Aeronautics and Space Administration to develop the control and guidance technology required for future space and aeronautical missions. The research objectives are reviewed, and by example, the nature of the efforts is shown.

Author

INTRODUCTION

The National Aeronautics and Space Administration is conducting a program of advanced research and technology development in order to pursue future aeronautical and space missions. As a part of this over-all program, control and guidance technology is developed. It is this control and guidance program that will be discussed

Future missions are difficult to define and no attempt is made to list them here. Required control and guidance technology for these missions is more clear, and several salient points are apparent. Many missions are of the sort typified by communications satellites, with only moderate control and guidance (C&G) performance needed, but with a premium placed on long life, reliability, and low system operating cost. Other missions, such as manned planetary exploration, will require high performance, along with very long life. The NASA C&G program looks to both sorts of requirements.

Underlying all of our C&G work is the requirement for great system reliability, in order to accomplish the mission. This mission accomplishment has aspects of performance, life time, installation cost and operating cost that must be optimized in some sense. Sub-optimal systems, simple reliable sensors, ultra reliable microcircuitry, and reproducible actuators are as necessary as highly precise shaft encoders or exotic computer programs.

Emphasis has been placed recently on design methods, both analytical and synthesis, for manned control of flight. Much use is made of modern control theory in this work, with current stress being on non-linear and stochastic behavior using state space methods. The end goal of this work is to develop a systematic approach to allocation of function and control/display design, in order to produce manned space and aeronautical vehicles that perform the assigned mission reliably.

Another characteristic of C&G requirements is that many related developments must be made available simultaneously for a system to be successful. For example, for a manned spacecraft, it is not enough to consider only the attitude control sub-system, but also the man's controls and displays, the over-all computation capability of the spacecraft, the trajectory, the navigation subsystem, the communications and tracking network, and the designers' tools such as theory and simulation must be considered in an integrated program.

With these ideas in mind, some specific tasks within the C&G program will be described. These tasks are conducted by NASA research scientists at nine NASA Centers, by industry, and by Universities.

EXAMPLES

The cryogenic superconductive gyroscope has been operated in a laboratory environment by industry under contract to Marshall Space Flight Center and by Jet Propulsion Laboratory with drift rates (errors) sufficiently low to demonstrate its feasibility and potential long life. Techniques have been established for measuring and reducing the AC power losses of the spherical rotor, which previously had deterred development progress. Successful demonstrations have been made of all-attitude frictionless levitation systems, stable spin-up and rotation of the rotor, and optical readout devices for detecting rotor orientation. Rotor levitation, used in tests by the Jet Propulsion Laboratory, is shown in Figure 1., and is typical for cryogenic gyroscopes. Actual drift data obtained from tests are also shown. Minute differences in rotors fabricated by the same construction methods, annealing treatments, and balancing techniques account for the wide variance in measured drift rates. The low drift rate of .056 degrees/hour for rotor MH2 is significant. Note the linear character of the errors; this provides for accurate prediction and, thus, compensation may be built in. In one test, the data fell on a straight line within ± .0013 degrees/hour. Effort is continuing to improve materials and fabrication techniques and optimize design parameters. The results should provide the basis for a reliable, high-performance gyro for long-term space flight use, especially when cryogenic fuels are carried aboard the spacecraft.

The use of earth or planetary horizons for both guidance and control suffers from a lack of precise knowledge of the exact horizon characteristics(1). To gather such knowledge, suborbital rocket experiments have been conducted(2), and further experiments are planned in the X-15 aircraft and in the Scanner vehicle. The four-channel radiometer used is shown in Fig. 2. Scanner will investigate the 14-16 and 20-40 micron bands with a vertical resolution of 0.03°. Future plans include long-term orbital experiments to investigate seasonal, topographical and geographical variations of the apparent horizon. Knowledge gained should allow the design of optimized horizon sensors for earth orbital use.

A star tracker currently being developed under contract to Goddard Space Flight Center utilizes advanced concepts of interest for future space applications. The sensor is a Channeltron image dissector, Fig. 3, which gives the same performance as a conventional photomultiplier tube, but is considerably smaller in size. The Channeltron concept substitutes a continuous surface of high resistivity for the multidynode stages of a photomultiplier. It is inherently more rugged and eliminates the voltage dividing network required by the photomultiplier. Also shown is a photograph of the star tracker which is being packaged for possible flight test in an Aerobee rocket. The tracker system uses a unique radial loop scanning pattern that combines high accuracy (15 arc seconds) and a wide field of view (8 degrees) in a single electronic scanning mode. A breadboard tracker has been completed and operated successfully in the laboratory. Development testing will continue.

A laboratory model of an optical radar for spacecraft rendezvous has been developed for Marshall Space Flight Center. The prototype, shown in Fig. 4, uses a combination of two-light sources; a high intensity xenon light and a gallium-arsenide laser. The xenon light acquires a target within a 12-degree field of view at ranges of approximately 17Km and tracks the target to a range of 3 Km. Below 3 Km, the gallium-arsenide diode mode is used. The spatial distribution of the diode light output is also shown. It is to be noted that the diode light output is relatively constant within a cone of 60° solid angle. This characteristic of the transmitter lends itself to simplified and reliable application in a spacecraft in that the sensor may be vehicle mounted without the use of gimbals. It appears possible to eliminate the xenon light by pulsing the gallium-arsenide source at a high rate. The maximum range of the optical radar is limited by the earth background; without earth background the range can be increased considerably. This remains to be investigated.

Computers comprise an integral part of onboard guidance and control systems. Development of magnetic logic computer technology is under way at the Jet Propulsion Laboratory. Magnetic logic computers offer potential advantages of reduced power consumption, increased resistance to temperature and radiation hazards, and improved reliability through the reduction of the number of active components utilized. Apparent limitations are primarily computation cycle time and methods for achieving non-destructive readout of stored information. Construction of a breadboard model was completed in 1964, and laboratory evaluation is currently under way. This computer is a rather slow speed, medium capacity general purpose computer, with emphasis on few active components. During the coming year, portions of the computer will be redesigned to incorporate modifications defined by the evaluation phase and to achieve a model suitable for flight qualification. Future plans include laboratory and flight evaluation of the redesigned model.

In spacecraft stabilized by gravity-gradient forces, very low control torques are encountered, and periods of oscillation of the vehicle are very long(3). Until recently, components for these vehicles such as bearings, dampers, etc., could not be tested on the ground in a representative environment. The Goddard Space Flight Center has developed a single axis simulator, Fig. 5, which now provides the correct environment. Equipment to be tested is mounted on the table, suspended from the ceiling mount by a metallic ribbon cable having a very low torsional restoring force. To further reduce the restoring force to levels comparable to gravity-gradient torques, twist of the ribbon is detected by an optical device (autocollimotor), and the upper end of the cable is rotated to maintain zero or a small constant maximum twist. This untwisting of the support ribbon causes the periods of oscillation and restoring forces to be comparable

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Superior numbers refer to similarly numbered references at the end of this paper.

to the levels experienced by a gravity-gradient stabilized vehicle in free space. By varying the inertia of the table through the addition of weights, the oscillatory periods can be controlled to give the two- to four-hour periods representative of the spacecraft period. In the zero torque mode, maximum torque unbalance levels can be similarly controlled to obtain torque levels of 4-8 hundred thousandths of an inch ounce. The simulator performance is several orders of magnitude better (i.e., lower torque unbalance for the zero torque mode, or longer period for the constant maximum torque mode) than has been heretofore possible. This will permit ground testing of gravity gradient satellite bearings and dampers at these torque levels and periods of oscillation experienced in orbit. Dampers and bearings for the Applications Technology Satellite[4] will be tested on this device.

Spacecraft subsystem developments are also required, such as a digital attitude control system with the potential for low drift, high accuracy, and high reliability. The advent of integrated electronic circuits makes this possible. There appears to be an absolute limit to the reliable accuracy of the analog approach as shown in the graph, Fig. 6. As the accuracy requirements approach .01 percent of the operating range, there is a sharp increase in complexity, and therefore a reduction in reliability, an effect not so limiting for lower "parts-count" digital systems. An advanced digital control system study has resulted in the fabrication of a single-axis spacecraft control system which has been successfully demonstrated through airbearing tests. The parts count has been reduced to 5% of that of the original. In addition to the equipment, mathematical models and synthesis methods have been developed. Additional effort is required for three-axis systems development.

Development of future guidance and navigation requirements is dependent on a continuing program of systems and trajectory analysis. Current efforts are: studies of simplified backup manned guidance systems which utilize the astronaut's capability to make navigational fixes and perform guidance corrections; continued attempts to develop closed-form guidance solutions for reducing computer requirements; studies of optimal[5] guidance system configurations for present and future missions; and the development of guidance requirements for lunar surface exploration.

Similarly, control theory and related applied mathematics is necessary for future control systems. The NASA is supporting considerable theoretical work, primarily in Universities, as a part of the nation-wide effort in this field. NASA supported efforts emphasize non-linear analysis and synthesis, optimization, sub-optimal designs, and stochastic and digital control. The theory is applied to problems such as control of large flexible launch vehicles, precise pointing of optical instrumentation, and economical attitude control of spacecraft.

Attitude control of a Manned Orbital Research Laboratory is under study.[6,7] Requirements for stabilization accuracy for a variety of modes of operation have been determined. The problem is complicated by movements of the crew within the MORL. Manual modes of operation for backup, emergency use, and for some primary functions have been studied using the simulator shown in Fig. 7. Preliminary results of these studies indicate that manual control modes can more than accomplish the mission. Very accurate pointing of experiments such as stellar photography require pointing accuracies in excess of those achievable today in the presence of crew movement disturbances. One one-hundred-thousandth of a degree is required here, while achievable accuracies are on the order of one-thousandth of a degree.[8] Future research will concentrate on solving these problems, from both the theoretical and hardware viewpoints. Advances in stochastic and time-varying control theory are needed. Specific components, such as digital momentum exchange devices, are being developed for possible use.

Work at the Langley Research Center has recently contributed directly to the Gemini project. The Rendezvous and Docking Simulation (RDS) has been used for this purpose[9], as well as contributing to the general technology of rendezvous and docking of space vehicles. The RDS is a man-carrying moveable spacecraft capsule arranged so that all of the vehicle motions that would occur during the final stages of rendezvous and docking can be duplicated. Fig. 8 shows the RDS carrying a Gemini capsule in the process of docking with an Agena mockup. Fourteen astronauts have "flown" in the simulator, obtaining training as a by-product of the research work. From the research, came improvements in the Gemini 3-axis hand controller, the Agena visual docking equipment, and improved lights for use during final docking. In addition the evaluation of some actual Gemini hardware was accomplished. This illustrates the close tie that can and must exist between the Research Centers and NASA flight projects.

To obtain data leading to more effective pilots displays, the recent development[10] of a light and accurate eye-movement camera affords a means of obtaining quantitative information that may be used in evaluation of the pilot's display, and ultimately increasing the systems reliability by insuring that the pilot reliably interprets

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the displayed data. A motion picture camera records both the scene being viewed and the exact fixation point of the eye on that scene, a white spot indicating the pilot's eye position. Fig. 9 shows a camera being worn by a pilot during a simulator flight at the Flight Research Center. On the upper right is shown a conventional X-15 aircraft display panel which provides fixed scales with moving-pointer indicators. The pilot's scan pattern is superimposed, as recorded during the first 40 seconds of a simulation of an X-15 launch. The pilot's task is primarily that of longitudinal control, as evidenced by the high level of concentration on pitch angle and angle of attack. The integrated contact analog display system shown on the left is a computer-driven television system that receives electrical signals from the vehicle's sensors and converts this information into a symbolic picture of the real world moving in six degrees of freedom, corresponding to the real world. The contact analog display lends itself to the superposition of additional information on the screen, such as null indicators or quantitative numerical information. Also depicted is the pilot's scan pattern while using the contact analog system during simulated X-15 launch. A comparison of the scan patterns shows that the pilot is able to obtain the required flight control information from the contact analog display with considerably less scanning. Shown last is a time history taken during a comparative evaluation of these displays for the simulated reentry portion of an X-15 flight. A preliminary evaluation indicates that the pilot's control precision in damping the vehicle's oscillations was improved when he used the contact analog display, verifying the conclusion drawn from the eye-movement camera data.

NASA and NASA contractors effectively employ a wide variety of dynamic flight simulators. Operation of, and data reduction for these remain complicated and expensive. Highly skilled pilots and astronauts are required to operate the simulators in order to obtain valid and relevant experimental results.[11, 12, 13] The efficiency can be increased by providing on-line digital computer data recording and analyzing facilities, which allows the experimenter to concentrate on the critical conditions of the experiment as they occur and by providing him with a more detailed and timely analysis of the data. A recently developed signal analyzer system is illustrated in Fig. 10. On the left is shown a simulator, which houses a pilot "flying" a problem. Also shown is the operating technician. On the right is the experimenter, at the digital computer console, which presents analyzed data on the TV picture to the right of the experimenter. Shown on the lower left is one of the system generated displays, which the experimenter uses to select the results to be viewed and to select any one of as many as ten different methods of analysis. One result that the system computes and displays immediately is shown on the right, a Bode plot of the human pilot's describing function. Illustrated are the pilot's phase lag (Ang) and attenuation (Mag) at various frequencies (W) as the pilot responds to the various components of the signal that he sees during a three-minute run. The graph was obtained in studies of pilot adaptive control characteristics.[14] This technique, soon to be applied on NASA simulators, has saved months in carrying out manual control experimental programs by allowing rapid isolation of the important parameters and conditions of a problem.

CONCLUSIONS

The control and guidance program described by example is varied, highly interdisciplinary, and keyed to future missions of NASA, as well as to a general advance in the state-of-the-art. It represents only a small portion of the C&G efforts in progress within the U.S. aerospace industry. It is intended to contribute to the technology available for future space and aeronautical missions through advanced research.

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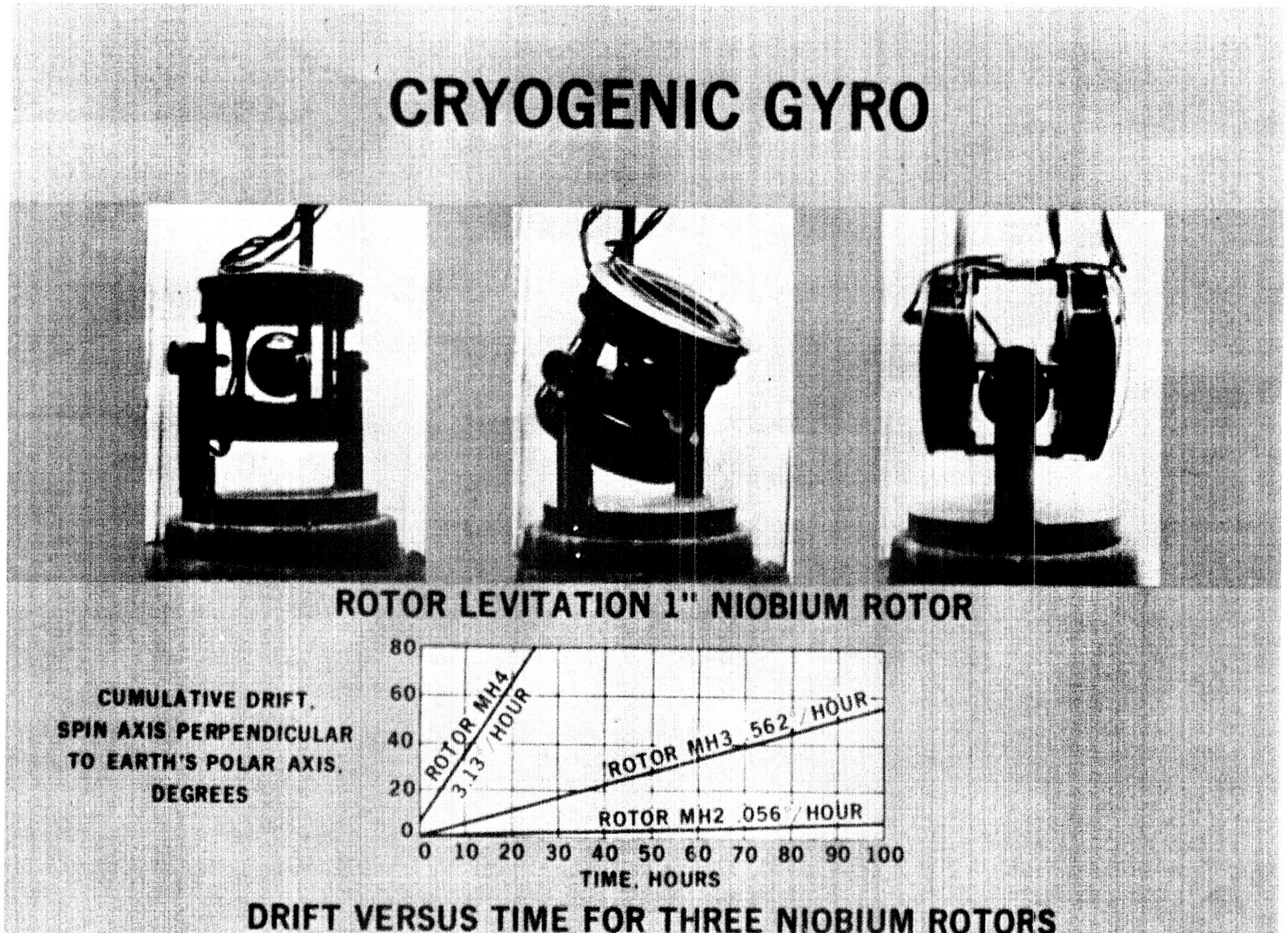

Figure 1

NASA RE 65-434
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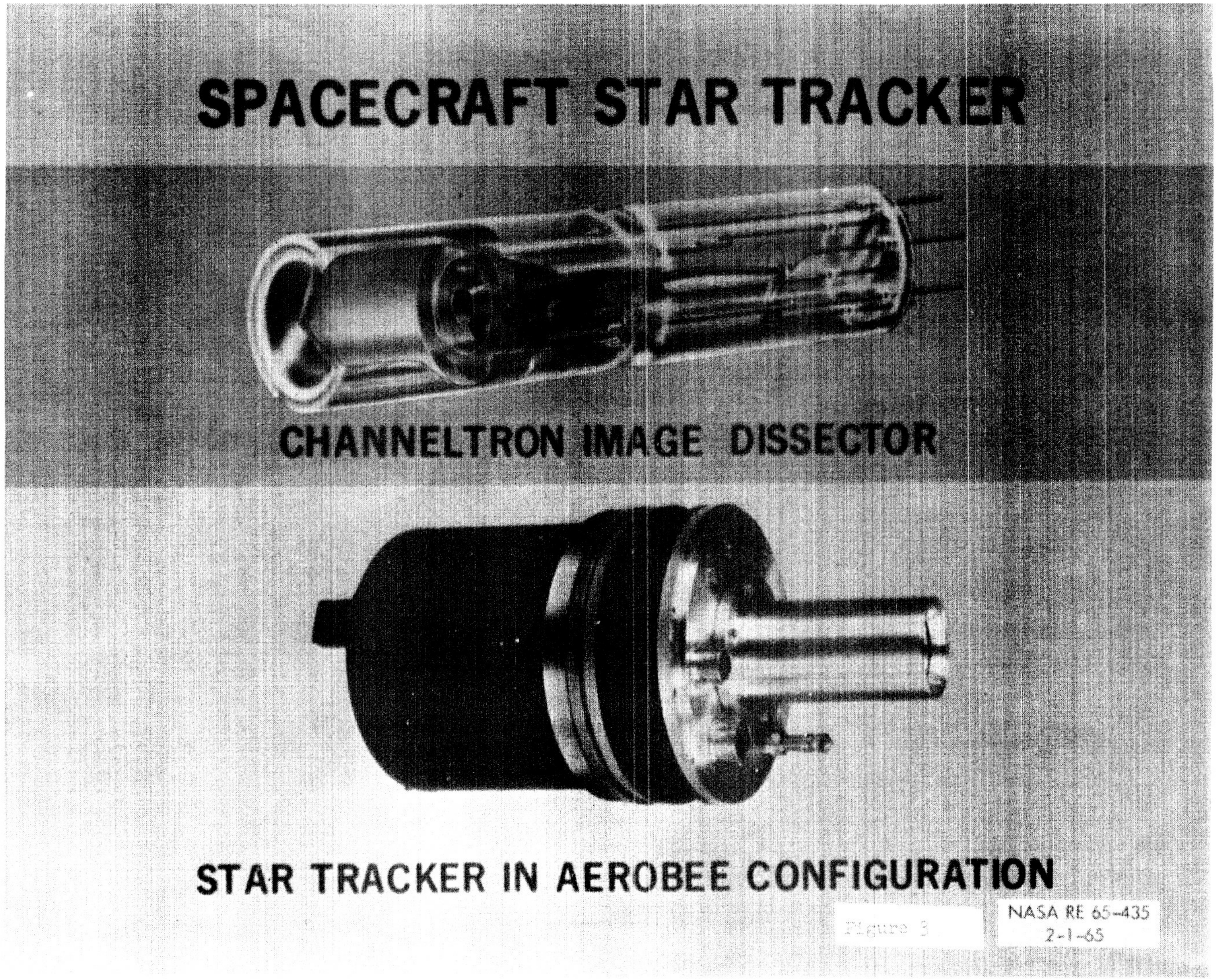
SPACECRAFT STAR TRACKER
CHANNELTRON IMAGE DISSECTOR
STAR TRACKER IN AEROBEE CONFIGURATION
Figure 3
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D-61 FOUR CHANNEL RADIOMETER

LANGLEY RESEARCH CENTER

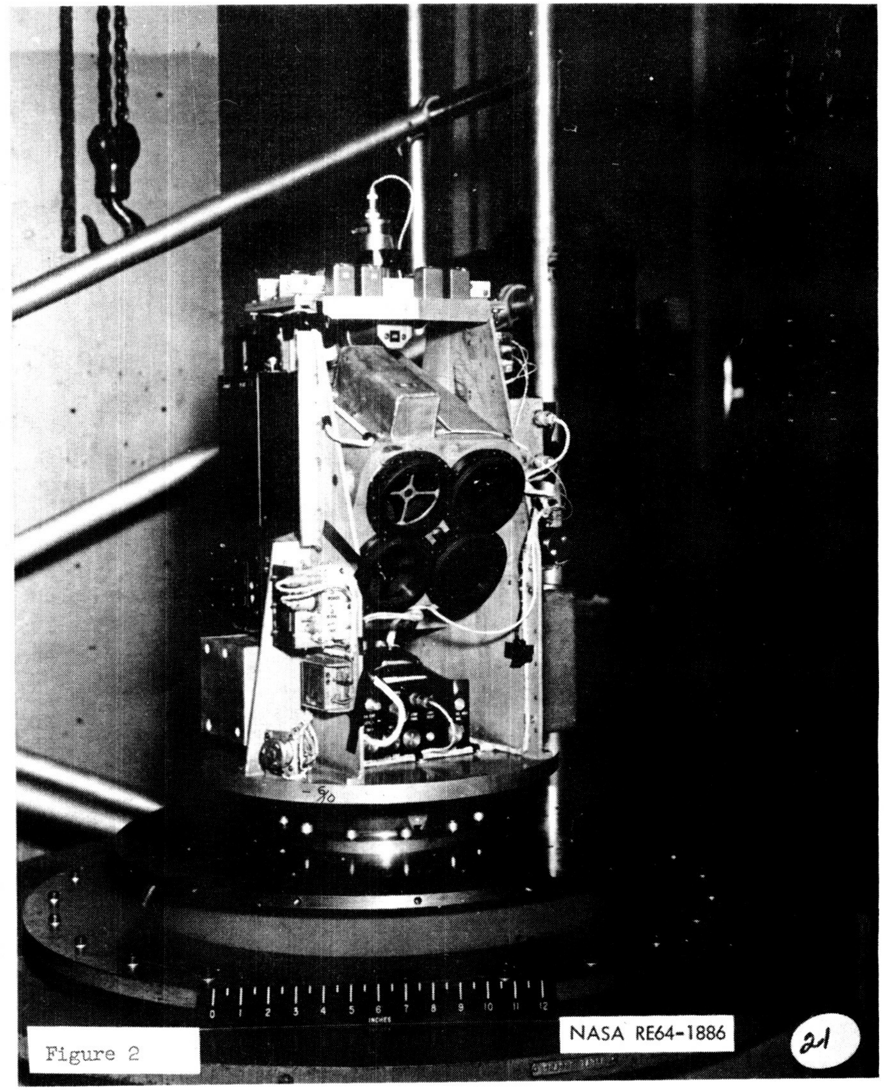
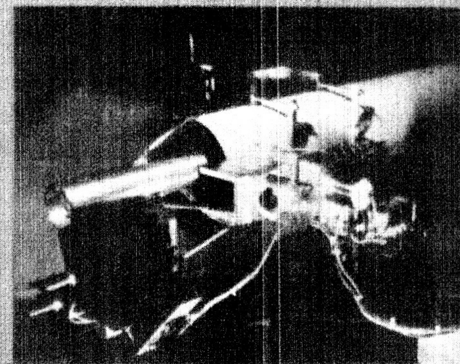
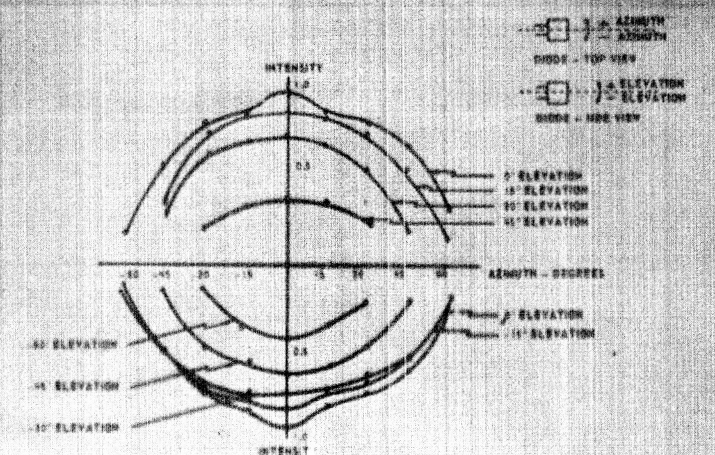


Figure 2

OPTICAL RADAR





SPATIAL DISTRIBUTION OF GALLIUM-ARSENIDE DIODE LIGHT

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Figure 4

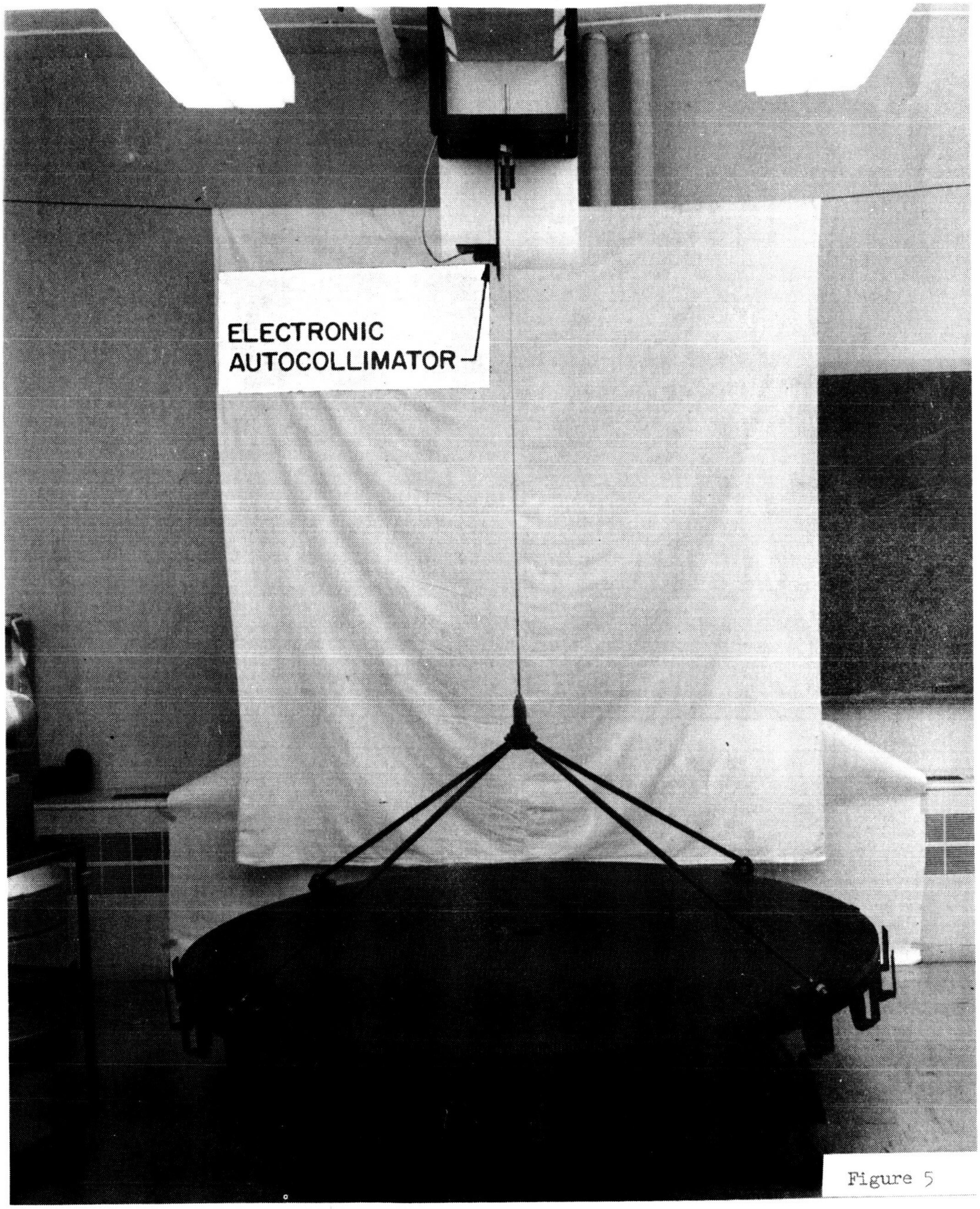

Figure 5

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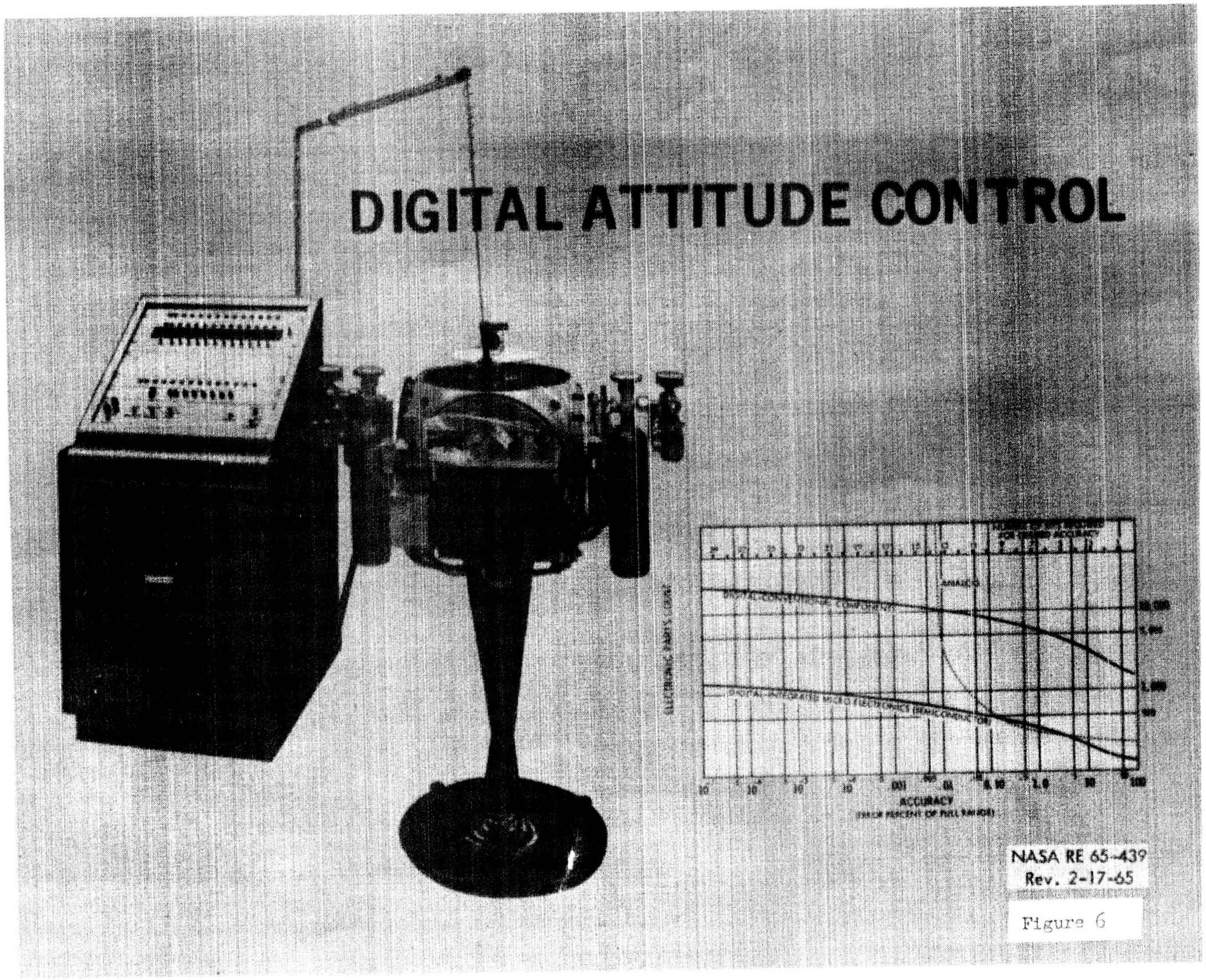

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Figure 6

Figure 7

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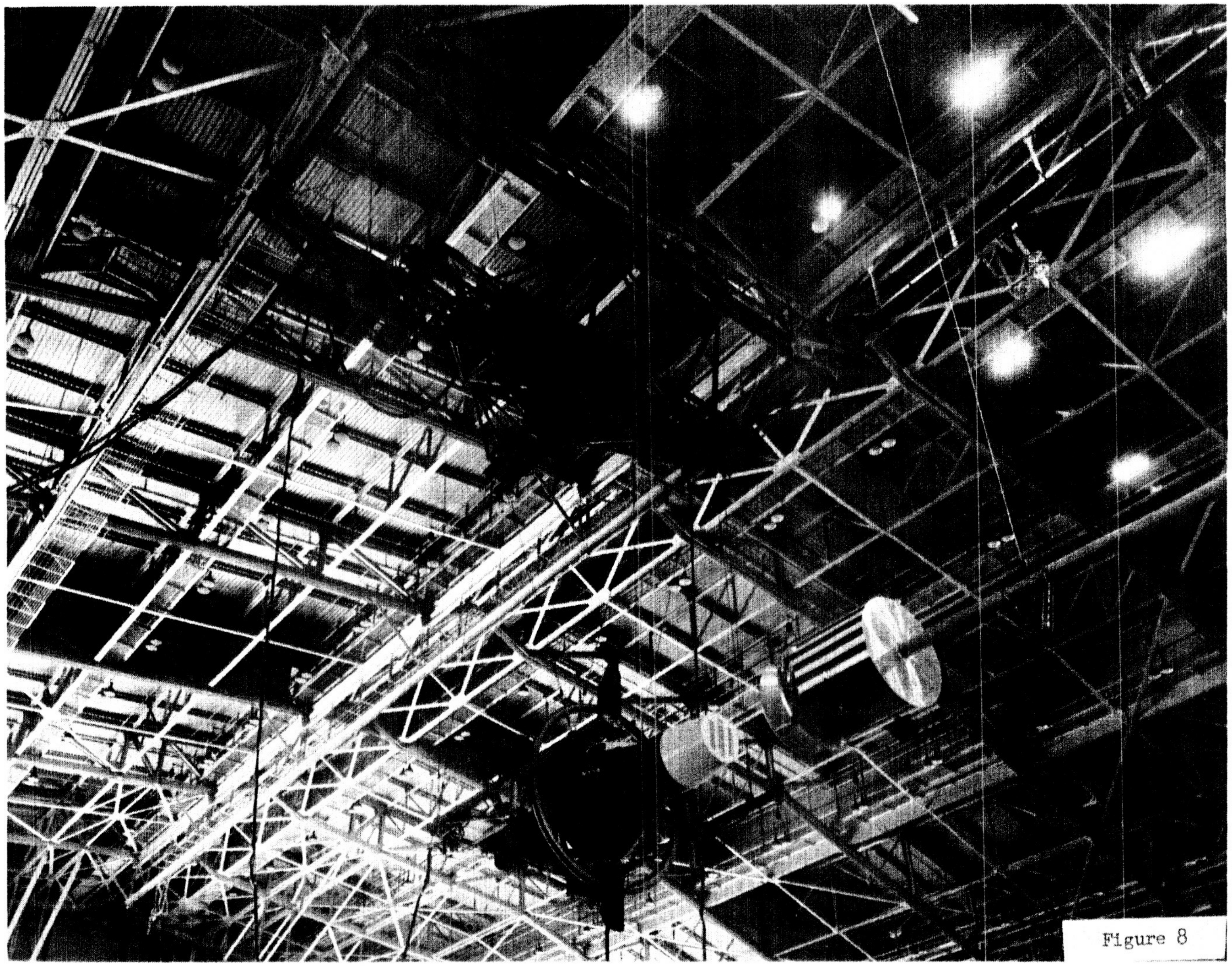

Figure 8

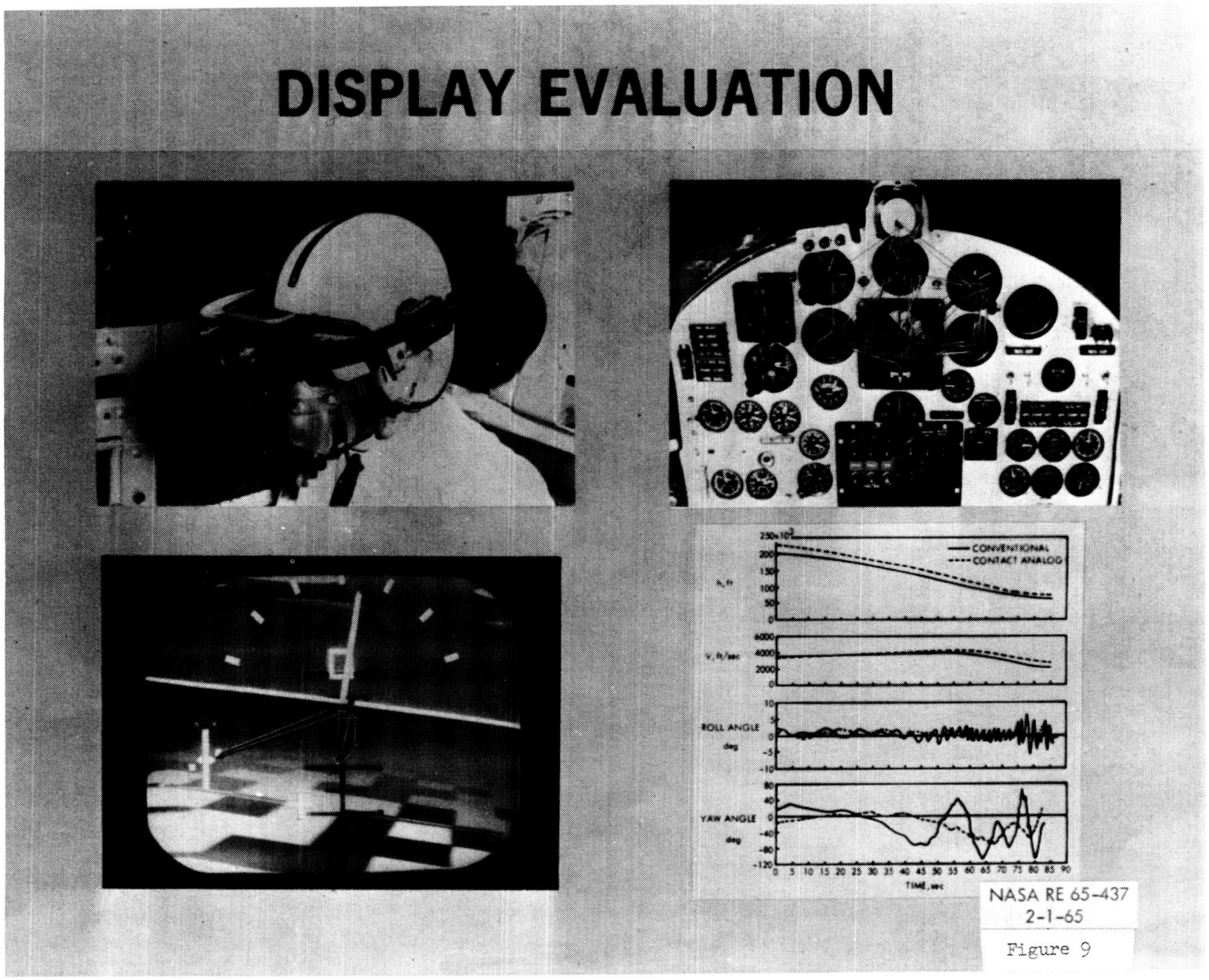

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Figure 9

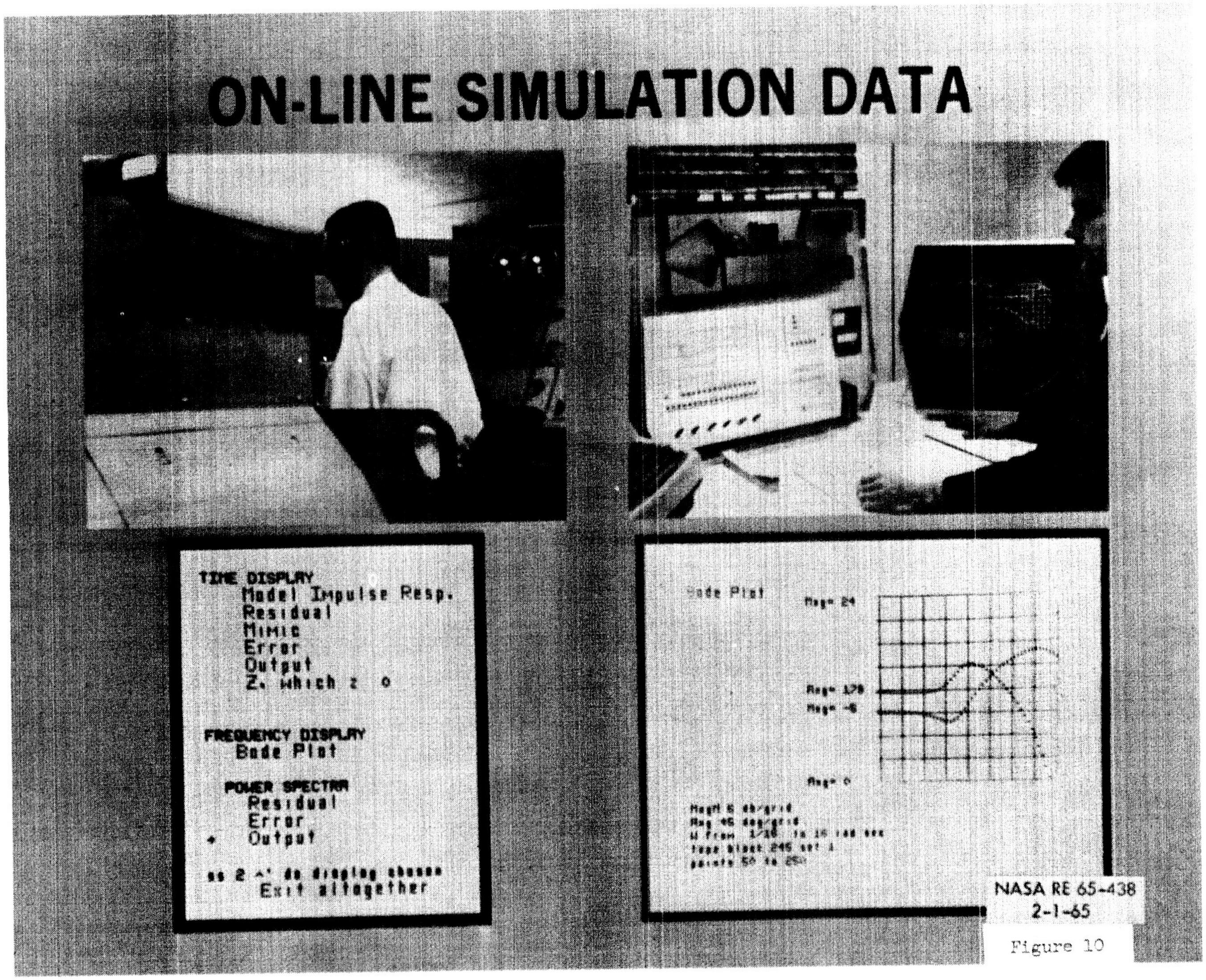

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Figure 10