FIRST STEPS TOWARD SPACE


EDITED BY
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Early Developments in Rocket and Spacecraft Performance, Guidance, and Instrumentation

ERNST A. STEINHOFF, United States

Introduction

Late in 1938, I was invited to join Dr. Wernher von Braun at Peenemünde, Germany, to take over the development of guidance and control systems for rocket vehicles and to direct activities in the areas of test instrumentation, flight testing, and flight performance measurements. My selection was based on the recommendation of Dr. Hermann Steuding at Peenemünde, a colleague and former head of the Flight Mechanics Department at the Deutsche Forschungsanstalt für Luftfahrt (DFS—German Research Institute for Motorless Flight) at Darmstadt, Germany. He felt that the work I was doing at DFS was directly applicable to the control of rockets and spacecraft.¹

The work performed in the period 1936–38 at DFS by myself and my teammates dealt with conceptual studies for guidance of high-volume-to-surface-ratio, rocket-propelled guided missiles; the analysis of strap-down gyro references on flight-path-oriented reference signals; and the study of the coordinate transfers required. We also worked on sensors for acceleration, rate of speed change, aerodynamic angle of attack; on measurement methods of angular rate and angular acceleration, and on the compensation for effects of angular rate and angular acceleration on flight-measurement equipment. Also conducted were experiments with autopilots and flight-control systems using these sensors; wind tunnel experiments with sensors in the flow field of the main body; tests of hydraulic amplifiers for control actuators in flight-control systems; and flight tests in aircraft of such systems suitable for missile application. About this time it became recognized that rate and acceleration measurements were needed to control with repeatable accuracy the flight paths of unmanned vehicles. Among the concepts worked on which found application and actual use in the post-1938 era were low-altitude recovery of missiles by using the rate of pitot pressure change to initiate the recovery sequence; use of angle-of-attack vanes to limit air loads under wind shear; the application of acceleration and rate sensors in addition to displacement sensors along with hydraulic servomotors to achieve the high response rates needed for repeatable guided-missile trajectories; and the use of the integration of acceleration for precision propulsion cut-off. Much of the pre-1938 flight-performance measurement, data acquisition, and evaluation at DFS were directly applied to subsequent rocket and missile work.

As a student working at DFS, I followed up earlier rocket-powered glider experiments of Friedrich Stamer.² While employed there, my group supported flight-performance measurements on a prototype of what later became the Me 163 of Alexander Lippisch (Figure 1).

Sensor Developments

The need to determine stability parameters for the flight performance of powered and unpowered aircraft became more and more urgent at DFS during the period 1936–38. The need for more accurate flight test instrumentation became obvious particularly under flight-test conditions, when an aircraft was towed by another aircraft to an altitude of from 3,000 to 4,000 meters, so that performance and stability parameters, independent of propeller interference, could be determined in the subsequent
glide flight. Dr. Werner Spilger, one of my teammates, developed a linear accelerometer (Figure 2), sensitive to a single measuring axis only, which deflected the mirror of an Askania 4-element optical recorder. The link between the mirror and the accelerometer mass consisted of a small metal channel with flexures of specific axis of rotation, so as to minimize the effect of the linkage of inertial components on the measured acceleration. These flexures caused real problems owing to the fatigue resulting from high frequency vibrations caused by boundary-layer separations.

Dr. Spilger at that time invented a link, consisting of a very small beryllium-copper alloy channel, flexible on the suspension points at each end. This solution proved very successful, and not only permitted measurement of large variations in linear acceleration, but also reproduced the fine structure of acceleration and vibration. These accelerometers (used in triplets with their axes mutually perpendicular to each other) were later used at Peenemunde for early rocket flight-path and velocity-control purposes. Because electric outputs rather than optical light-beam deflections were needed to produce the control signals for flight-control equipment, pickups were developed which used a differential change in capacity ratio or differential impedance to produce the desired signal.

While he was at Darmstadt Institute of Technology, Dr. Helmut Schlitt, later at Peenemunde, originally used the same type of accelerometer to develop a lateral inertial flight-path control for missiles. However, he changed the pickup to an a.c. current-modulation system, the current was proportional to lateral acceleration and the integral of the current proportional to the lateral velocity.

For stability measurements, of interest were not only deviations in attitude and the easily determinable damping increment—to determine deviation from linear behavior during flight-path oscillations—but also the angular rates, angular accelerations, and angle of attack. Also important were changes in pitot pressure during, for instance, a complete phugoid oscillation cycle, and changes in actual attitude to account for all effects either observed or recorded.

Although rate gyros were initially satisfactory to determine pitch, yaw and roll rates, their own deflection introduced errors due to their finite spring constants. Introduction of angular accelerometers—in which was measured the torque of an inertial mass constrained to movement in one axis of rotation—permitted resolving errors of angular rates and attitudes. Since, particularly for phugoid analysis, angles of attack were of importance, a dual-vane angle-of-attack meter was developed. Due to the inertia of the vanes, this instrument was sensitive to angular accelerations and gave reading errors proportional to the instantaneous acceleration; it also tended to oscillate. To eliminate this effect, a rotating mass of equal inertia was installed, with its steel wire pulleys reversing the sense of rotation of the compensating mass torque. If no aerodynamic forces were acting, and only angular acceleration tended to displace the angle-of-attack meter, the inertia of the compensator prevented any deflection. In the event of the presence of aerodynamic forces, these permitted proper rotation of the angular acceleration compensation and the angle-of-attack meter. With this arrangement, angular acceleration effects on angle-of-attack measurements were satisfactorily eliminated, but its overall inertia to aerodynamic forces was twice as high as that of the vane alone.

In order to measure the actual pitch displacement, either optical cinetheodolite measurements
**Figure 2.**—a, Rear view of Askania light beam optical recorder with acceleration sensor in lower left side. Three other instruments are ambient pressure, pitot pressure and rate of climb. b, Sensor traces of Askania optical recorder. c, Linear accelerometer element on instrument mount. Accelerations deflect light beam by deflecting mirror. d, Linear accelerometer sensor for Askania 4-trace optical recorder. e, Accelerometer sensor installed in housing. Deflectable mirror in center. Photos courtesy Dr. W. Spilger.
of high resolution or barometric measurements of equally high (or even higher) resolutions were needed. Neither existing altimeters nor rate-of-climb indicators were adequate at that time to measure vertical displacement of the order of only a few feet or meters. To solve this problem, the author started the development of a rate-of-climb indicator in which the pressure gauge consisted of a single grounded corrugated beryllium-copper diaphragm (Figure 3). This diaphragm acted as a variable capacitance insulated between two electrodes, the measuring volume of which was connected with the ambient pressure source, and the other volume was connected with a 250-cc reference air volume within a thermos bottle. Both volumes were interconnected by a capillary such that the time constant of the rate indicator was in the order of 10 milliseconds. The capillary could be closed off so that a sensitive statoscope could be obtained which permitted horizontal flight within a meter of a reference altitude.

The same technique was applied to obtain either a pitot pressure rate-of-change indicator or a stagnation pressure variometer. This type of instrument was later used at Peenemunde to arm the parachute recovery system of A-5 missiles during the ascent flight path; it released the brake and later the main parachute at certain stagnation pressure conditions, based on the rate of change of pitot pressure rather than fixed altitude. This method proved more dependable and desirable than using an altimeter to initiate the recovery sequence.

While stabilized platforms were under development for missile use during this period—at Kreisgelarete, under the direction of Captain Johan M. Boykow—these were too bulky to be installed in the aircraft we had to test. We therefore attached to the vehicle (strap-down system) conventional single- and two-axis-free gyros, mounting them in three mutually perpendicular axes (directional and horizon gyro arrangement). To resolve gyro readings and to determine actual displacement angles referred to the flight path (rather than the inertial reference axes), coordinate transfer equations were derived and published. These equations established the relation between gyro read-out and actual attitudes with reference to the flight path. Later, in 1939 and 1940 at Peenemunde, this system was further expanded to determine proper propulsion and cut-off velocities through reference axes fixed to the body axes.

At that time the author proposed to improve such systems by use of thrust-control to make the trajectories more reproducible and to reduce the range errors of such systems. This approach compensated for the effect of time variation on cutoff velocity, as proposed at that time by Dr. Walter Schwidetzki. Much of the refinement of the theoretical analysis of these techniques was later performed by the Institute of Practical Mathematics of the Darmstadt Institute of Technology under Professor Dr. Alvin Walther, and at Professor Wilhelm Wolman's Electronic Institute at the Dresden Institute of Technology. Also Dr. Steuding, one of my colleagues at Darmstadt, continued much of his work at Peenemunde and made major theoretical and practical contributions to the state of the art of that time. One of the results of his work was that, for the A-series type of missile (A-3 to A-8), positive stabilization and flight control was introduced in the period 1938–39. The originally considered mode of spin stabilization was abandoned, because of its sensitivity to wind shear in ascent and descent.
During measurement of aircraft flight performance, knowledge of the actual angle of attack is of great value for the analysis and interpretation of flight-performance data. In addition, angle-of-attack meters can also be used to limit or control the range of angle of attack. While working at DFS at Darmstadt, I used the above-described angle-of-attack meter to limit the angle-of-attack range during high-speed cruise, which reduced structural loads due to gusts. I also introduced the angle-of-attack reading to bias gyro displacements on an hydraulic or pneumatic autopilot. Another bias was the pitot pressure rate of change. Both techniques led to flight control modes more closely related to the pilot's feel of flying. Particularly, limitation of angle of attack to a prescribed range can reduce structural loads. Therefore this method was considered at Peenemunde to limit the angle of attack to reduce the structural weight of the missile. Since theoretical analysis showed that lateral forces, angle of attack, and speed or stagnation pressure have mutual relations, the angle-of-attack measurement was replaced by normal force measurement and the velocity measurement was replaced by electronic means. However, wind-shear reduction by installing angle-of-attack vanes for the bias of autopilots was later used again by my colleagues on the Redstone missile at Huntsville, Alabama.

Many of the thoughts derived in flight-performance testing at Darmstadt were actually put to use at Peenemunde by one of my colleagues, also from the Darmstadt Institute of Technology, Dr. Helmut Hoelzer. The use of accelerometers and rate indicators induced him to find electronic methods of integrating and differentiating sensor displacements, and to mix the results in accordance with stability requirements. His familiarity with Dr. Harry Nyquist's work then led to applications which, late in 1939, resulted in possibly the first electronic analog computer to simulate flight performance in the laboratories, rather than through tedious and time-consuming flight tests or static tests, and resulted in simplification of autopilots. This work eventually led to the A-4, or V-2, autopilot, which was fully electronic.

**Flight Control Developments**

During the 1936–38 period, the author worked to improve flight and landing qualities of single-engine aircraft by using angle-of-attack meters in connection with pneumatic amplifiers. Experience with these techniques, and having observed the need for higher response rates in missile applications, later led me to use hydraulic amplifiers. During this period, close contact developed with Askania-Berlin in pneumatic as well as hydraulic servo applications. This cooperation led to the modification of hydraulic servomotors to meet response and torque requirements of control actuators on the A-4 and A-5 missiles at Peenemunde. The original servomotors were improved to torques several times their original torque rating through mutual programs which increased control response and dynamic range of controllability. The A-5, Wasserfall and A-4 flew with these servomotors. Parallel work with Siemens was also successful, permitting alternate use of Siemens actuators. Insight gained in flight performance testing also found application during the 1939–40 period in beam-riding systems flight tested in aircraft.

**Flight Performance Measurements**

Next in importance to sensor developments for facilitating measurement of flight performance, was the development of ground-based optical equipment—the ballistic cameras and cinetheodolites which later played an increasingly important role in missile and rocket development testing. Wilhelm Harth and Dr. Paul Raetjen who, at DFS during the period 1931–39, devoted considerable time to the improvement of optical precision equipment, sponsored the development of what became cinetheodolites for flight performance measurement. The original design was an intermediate of the ballistic camera and the well-known Askania cinetheodolite (Figure 4). In this design the target was tracked and superimposed on a precision-grid fixed background, as shown in Figure 5. In order to achieve the required high resolution, the graduation of a hollow hemisphere required a mechanical skill available in only a few precision mechanics. This was a biggest obstacle to serial production of these cameras. Harth's efforts and Askania's design capabilities led to the later well-known Askania ballistic cameras and the Kth 39 and Kth 141 models used at Peenemunde and later at many other missile proving grounds.

However, the use of on-board recording and
Ground-tracking led to another technological development of even greater importance. While at DFS (1931-33 and 1936-39), I worked on airborne communication transponders and transmitters for transmitting messages from aircraft to aircraft, and aircraft to ground. The transmission of instantaneous sensor data was the next step to make flight performance measurement more efficient. At Darmstadt we only pondered how to combine these various techniques to achieve an autonomous data system. However, Dr. Gerhard Reisig at Peenemunde, together with Dr. Rudolf Hell at Berlin-Dahlem, developed the first missile-borne recorder, using a picture tube to electronically present sensor data by sub-commutating it to read-out, and to photograph traces of a multitude of sensor data. The next step was to be radio transmission to the ground.

Even prior to World War II, work on pulse time, pulse code, AM-telemetry and possibly also AM/FM and FM/FM were not only on the drawing board, but in laboratory tests. Team members participating in this effort, which I coordinated from 1939 on, were Dr. Reisig, Dr. Hans-Heinrich Emschermann, Dr. Hans J. Rittinghausen, and Dipl. Ing. Helmut Gröttrup.

In 1938 one of the tasks we handled in our flight performance group was the engineless prototype (see Figure I) of what later became the Me 163. This prototype aircraft, designed by Alexander Lippisch and his team, did not yet have its rocket engine. While waiting for the completion of its development, it underwent considerable flight testing with Rudi Opitz as test pilot. During one of these test flights, Opitz had extreme difficulties in recovering the aircraft from a spin, and had to bail out at an altitude below 100 meters. My colleagues and I saw the parachute blossoming at the time Opitz disappeared in the forest surrounding our test center. We were amazed to find him alive, although badly shaken emotionally. He told us later that because his parachute did not sufficiently decelerate his fall, he spread himself out during the fall and tried to catch some branches of the fir trees he was falling through; these he managed to hang on to until the parachute lines started to stretch. The force of the impact would still have been too great, however, if the moss and soft soil had not further moderated his impact. The German Army officers, arriving at the scene, asked Opitz if they could be of any help. Opitz replied: “If you should have a cigarette, it will help me most.” We were glad to see him alive. Rudi Opitz has recently recovered from a severe helicopter accident, which he sustained while a test pilot at Lycoming. His 14-year-old son, like his father, is an ardent glider pilot and looks forward to becoming a test pilot.
First Personal Involvement with a Missile

It must have been in 1937 or 1938 when my team was asked to look into conceptual solutions for an air-to-surface missile which would be dropped out of the bomb bay of a conventional bomber, and which would be controlled or could be guided to its target. Being familiar with our institute's prior work with rocket propulsion (Friedrich Stamer's pioneering work at the Wasserkuppe), we decided that this vehicle could be either rocket-propelled or unpropelled, since space available and other dimensional constraints indicated that no wings could be used. In contrast to Lippisch's approach, we selected solid-fueled motors of the type used by German Army units for rocket propulsion. About two years later I used the same type for missile firings from my brother's submerged submarine. Instead of using the conventional body of revolution approach, we selected a low-aspect-ratio (AR = 0.5) lifting-body configuration operating within the subsonic speed range. The project never went beyond its initial conceptual analysis because I left for Peenemunde soon after the beginning of this work. However, other solutions were later dealt with by various DFS personnel. Alexander Lippisch's Me 163 rocket airplane became one of the major projects to be tested in subsequent years at Peenemunde.

Flight Dynamics Aspects of Flight Testing Work

Many of the problem areas which later became key issues in missile developments, hinted at their importance early in the flight-performance work at the DFS because of the considerable attention given to flight handling qualities; to judgment of interaction between configuration peculiarities, flight performance, and flight handling; as well as to mutual interference between powerplants, aerodynamics, and stability. The realization that many parameters other than attitude, speed, and altitude represented the complex dynamic behavior of missiles and aircraft, led to the development of many types of sensors in order to obtain a better insight into areas of flight dynamics, the importance of response rates, and the requirements on control parameters. Consequently much work was going on during the 1936–38 period in quite a few laboratories. Dr. Oppelt at the DVL, Dipl. Ing. Waldemar Moeller at Askania, Dr. Wilfried Fieber and Dr. Gerald Klein at Siemens, all worked on different solutions to the same problems, and they were able to fill in the gaps we found at Peenemunde one to two years later.

Also during this time, as the theory of flight dynamics was perfected, it was learned that with higher speed and required tighter flight-path control, the response rate of contemporary autopilots was insufficient. The importance of the higher derivatives of sensor displacement became more and more obvious. The need to reduce lag in the control circuits and to improve damping coefficients became increasingly accepted. Dr. Oppelt, Prof. Dr. Maximilian Schuler, Prof. Dr. Kurt Magnus, and Dr. Steuding were key individuals in developing the theoretical background needed to assist Dr. Hoelzer and his team in finding the electronic circuits most suitable to meet these requirements.

The Challenge of Inertial Reference Systems

At the time that Dr. Paul von Handel, Dr. Johannes Plendl, and others conceived fundamental radio navigation systems, it became obvious that these systems could not cover all the needs of the advancing fields of rocketry and aeronautics. At a time when we found that radio propagation through rocket exhaust had its problems, Dr. von Braun and Captain Boykow discussed the potential of fully inertial platforms and the use of Professor Schuler's earth radius pendulum for rocket and spacecraft navigation. At the DVL, tests of aircraft navigation devices showed that the most difficult areas of technological requirements were those involving gyro drift and inaccuracy of accelerators. I am told that an aircraft, departing from Adlershof near Berlin and approaching the Netherland border, indicated “Australia” on its navigation system as the current position.

Drift rates of gyros produced at Kreiselgeräte, Berlin, reduced drift rates to below a degree per hour; platform designs, using “Schulerloops” progressed subsequently to the point to be flown in V-2s during 1943. While strapdown systems, as initially used at Darmstadt, appeared to be no match to gyro-stabilized space-reference systems, there are many applications in which these still hold their own. Progress made in digital computers has contributed much to their improvement, in-
dividual gyro and accelerometer performance being of equal importance in each application. Also the two original modes of air- and fluid-suspended gyros are still in competition with each other, the former originally sponsored by Kreiselgeräte and the latter by Siemens.

Much of the research in the area of gyro-platform improvement and error-source analysis has been performed by an outstanding U.S. scientist, Dr. Charles S. Draper, and his team, who, as the current president of the International Academy of Astronautics, is the chairman of this Symposium. The current state of the art in this field owes much to Dr. Draper and his group at the Massachusetts Institute of Technology.8 I am proud to pay him this tribute at this time and place.

Rocket Engine Developments at Kummersdorf

While I personally was not involved in rocket-engine development, I became involved in the instrumentation and analysis of rocket-engine tests and data transmission to a central recording station near the end of the period covered in this presentation. In this connection, I would like to report on the development work of some of my colleagues at Kummersdorf and Peenemunde which I think was fundamental in rocket-engine development and therefore deserves mention on this occasion.

From 1937 through 1939, a 1500-kg thrust high-pressure rocket engine (750 psi or 50 kg/cm²) was developed in which aluminum was used for the combustion chamber and exit nozzle. This required cooling of the entire chamber and nozzle. In order to accomplish this, transpiration cooling was introduced to produce a fuel-rich, cool envelope surrounding the hot combustion gases (2200° to 2400°C depending on the fuel and oxidizer selection), to protect the chamber itself. The introduction of this technique, to be credited to Dr. Walter Thiel, Klaus Riedel, Dr. h. c. Arthur Rudolf, Mr. Albert Püllen-berg and others, is one which brought rocket-engine technology a substantial step forward and could be classed the first modern rocket engine.

My team’s involvement toward the end of our work at Peenemunde also dealt with flame temperature measurements, exhaust gas composition measurements and causes of radio-transmission blackout. For some of this work, my organization issued research contracts to groups of universities, supporting our work. Use of sodium-D line reversal technique to determine flame temperature was one of the new techniques in which Dr. Martin Schilling was instrumental.

Summary

The preceding paragraphs are an historical account of the developments and contributions made by the author and his team to the instrumentation, flight testing, flight dynamics, guidance, and control of missiles. Broad technological fields provided initial answers to many technical and developmental problems; they also outlined the avenues along which much of the subsequent research would have to be directed before it could meet the increasingly difficult requirements resulting from supersonic flight through dense and rarefied atmospheres.

It is not possible to credit every person who was involved in this effort. My account must be a tribute to those who were not individually named, but whose contributions provided the multitude of scientific and engineering building blocks. As to my own contributions, I was at all times supported by dedicated teams and colleagues of exceptional training for the tasks assigned to them.

In addition to particularly crediting Dr. Draper, I feel compelled to give credit to Dr. Wernher von Braun, whose broad engineering abilities, exceptional insight into the entire spectrum of missile and spaceflight, and whose broadminded leadership permitted me, subsequent to 1938, to implement the many solutions found prior to that time for missile and spaceflight guidance applications.

NOTES


2. The early tests by Friedrich Stamer and Alex Lippisch
on the Wasserkuppe, one of the Rhön Mountains in Western Germany, are described in Willy Ley's *Rockets, Missiles, and Men in Space* (New York: The Viking Press, 1968), pp. 419-21.—Ed.


5. See note 2.

6. Dornberger, V-2 (see note 2), p. 245.—Ed.
