The Computing Boom in the US Aeronautical Industry, 1945–1965.

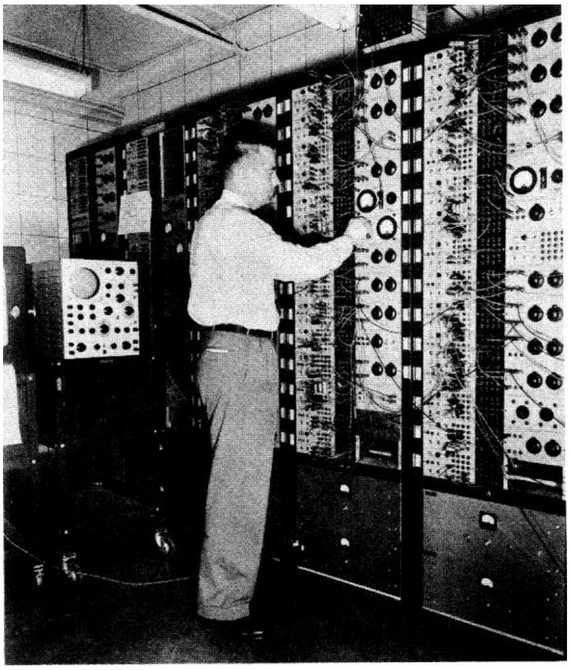

Figure 1: The Boeing Electronic Analogue Computer 1950
(Source: Henry Paynter: Palimpsest on the Electronic Art, Boston 1955, p. 44)

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Content

1 Introduction

Whereas standard accounts on the history of modern computing tell the development of the digital computer as an isolated event on the East Coast of the US, this paper will show the history of machine computing in the context of the broad and rapid development of aeronautical weapons in the US military since 1945. Analogue computing plays an important role that is nearly completely ignored by standard accounts. The extensive literature on the history of electronic digital computers does not take into account the special history of computing machines that the US aircraft and missile industry employed from 1945 to 1965.

In their accounts of the history of electronic digital computers, the authors Martin Campbell–Kelly, William Aspray, Paul Ceruzzi and Atsushi Akera show linear success stories.[1] But the authors do not consider the wide variety of electronic analogue computers that arose from 1945 to 1965, and their application in the US aircraft and missile industry, especially clustered around Los Angeles. In his account of computer applications in this industry, Paul Ceruzzi made only a short note on analogue computing. The aeronautical industry, however, made great use of it. The lack of analogue computers in standard accounts is surprising, insofar as the military strength of the US was based on a strong air force and a large fleet of aircraft carriers furnished with advanced fighting airplanes and missiles. But these weapons were developed and produced in the aircraft industry, with its greatest concentration in and around Los Angeles. In this paper, I will show that the advancement of this industry relied more on engineering supported by analogue computing than on high speed electronic digital computers that were developed by mathematicians on the East Coast for academic purposes. In the historiography of technology, the prestige of John von Neumann was used to exaggerate the importance of the digital computer. Uncritically Thomas Hughes linked von Neumann's role in the Intercontinental Ballistic Missile Advisory Committee to the claim that the trajectory of the Atlas rocket was calculated with the digital computer, even though large batteries of analogue computers were used in rocket research.[2] The MIT book series *History of Computing* does not offer a book on analogue computing.

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[1] Martin Campbell-Kelly, William Aspray, Nathan Ensmenger and Jeffrey Yost, *Computer – A History of the Information Machine*, (New York, 1996, 2014). Atsushi Akera, *Calculating a Natural World - Scientists, Engineers, and Computing during the Rise of U.S. Cold War Research*, MIT Press 2007. Paul Ceruzzi, *A History of Modern Computing*, Cambridge, Mass., 2000.

[2] Paul Ceruzzi, *Beyond the Limits. Flight enters the Computer Age*, MIT Press 1989, 57, 63. Thomas Hughes, *Rescuing Prometheus*, New York 1998, 85.

On the emergence of electronic analogue computers from 1945 to 1955, Small has already made a broad study.[3] I will begin with this study by providing additional examples of the application of electronic analogue computers in the aircraft industry, in a military context. I will show the development of new types of weapons: fighter airplanes with jet propulsion, anti aircraft missiles, ballistic missiles and guided missiles. I will distinguish the special fields in which analogue or digital computers can be applied. I will show the way in which the aircraft industry applied digital computing parallel to analogue computing. Then, I will show the cautious steps towards digital computing in the aircraft and missile industry, from the IBM 604 punch card machine, to slow digital computers with drums, to high speed digital computers. I will give some evidence to show that it was not before 1957 that an airplane was flown which was designed with the aid of a high speed digital computer. Up to 1970, this kind of computer did not replace the electronic analogue computers that were needed throughout the design process of the aircraft and missile industry. In addition, in missile and space programs, electronic analogue computers prevailed in Air Force research centres, and in those of NASA. For example, in the research centre in Langley, Virginia, NASA set up a large, all-purpose analogue computer for the Mercury project in 1960.[4] In the 1980s the digital computers achieved a performance in simulation studies that were comparable to analogue ones. The excellent analogue computer complex at NASA's Langley Research Center was discontinued in 1990 because of lack of use.[5]

As primary sources, this paper relies upon contemporary machine computing journals, as Mathematical Tables and other Aids of Computation, on the Newsletter on Digital Computers of the Office Naval Research, on the Proceedings of the Radio Institute Engineers (IRE) and the Transactions of the American Institute of Electrical Engineers (AIEE). In addition, the paper draws on surveys on the development of computers around the year 1950 which the Ballistic Research Laboratory in Aberdeen and the ERA corporation have provided. Furthermore, I refer to the Computer History Museum in Mountain View, the National Museum of the USAF and to the Analog Computer Museum, Library, Bad Schwalbach, Germany. I also used the collection of reprinted papers on analogue computing that Henry Paynter edited in 1955.[6]

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3 James Small, *Analogue Alternative. The Electronic Analogue Computer in Britain and the USA, 1930–1975*, London 2001. James Small, 'General Purpose Electronic Analog Computing: 1945–1965', IEEE Annales of the History of Computing, Vol. 15 (1993), No.2, 8–18. Chris Bissell, *A great disappearing act: the electronic analogue computer*, IEEE Conference on the History of Electronics, 28-30 June, 2004, Bletchley, UK.
4 Datamation, 1961, May, 8. For the social history of computing at Langley see Margot Shetterly, *Hidden figures: The untold story of the African American women who helped win the space race*, London 2017.
[5] Hewitt Philips, *Journey in aeronautical research: A Career at NASA Langley Research Center*, Monographs in Aerospace History, Number 12, Chapter 6, Washington, D.C., 1998.
6 Henry Paynter, *A Palimpsest on the Electronic Analog Art*, Boston 1955.

For the following, a distinction between analogue and digital computers is required, as these kinds of computers developed to a field of competition. An analogue computer is a physical analogue to the problem it solves. Its spread grows with the complexity of the problem. When the problem is simple, the analogue computer also remains simple. An analogue computer gets its input from electrical and mechanical sensors that measure the variables of interest as physical quantities, as shaft rotation, electrical resistance, frequency, etc. According to Bernd Ulmann, an analogue computer is a piece of equipment whose components can be arranged to satisfy a given set of equations, usually simultaneous ordinary differential equations.[7] As an electronic analogue computer one can regard an analogue computer that was based on the DC–amplifier. The debate at the beginning of the 1950s distinguished between small electronic analogue computers and large systems in the flight simulation of missiles and aircrafts.

As opposed to analogue computers that focus on the analogues of physical systems, digital computers focus on numerical problems that can be solved by a sequence of elementary arithmetic operations. Digital computers receive input data as a stream of numbers supplied by punched cards or tapes, and stored in memories as numbers of base 10, base 5 or base 2. The memory technology developed from relay-based memories to electronic ones was based on flipflop tubes, William tubes, mercury delay lines, and later, magnetic drums or cores. Besides the memory unit, digital computers possessed a control unit to execute the commands of a program and an arithmetic unit which performs elementary arithmetic operations on numbers. The technology of the arithmetic unit changed from relay technology to electronic circuits with electronic tubes, which could perform arithmetic operations very quickly in a range of microseconds. Examples of early digital computers with an electronic arithmetic unit are the ENIAC (Electronic Numerical Integrator and Computer) in 1945, IBM‘s SSEC (Selective Sequence Electronic Calculator) in 1948 and the SEAC (Standard Eastern Automatic Computer) in 1950.[8]

In the literature, is not known to which fields digital or analogue computers can be applied. To fill this gap, I will give an overview here. Digital computers were very useful in arithmetic calculations, for example, the determination of large prime numbers,[9] inversion of a matrix, multiplying matrices and

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[7] Bernd Ulmann, *Analog Computing*, Oldenbourg Publisher, Munich 2013, 2.

[8] For the SSEC see Charles Bashe, ‘The SSEC in Historical Perspective’, *IEEE Annals of the History of Computing*, vol. 4, 1982, issue 4, 296-312. For the ENIAC see Thomas Haigh, Mark Priestley and Crispin Rope, *ENIAC in Action*, Cambridge, Mass., 2016. On the SEAC see S. Alexander, ‘The National Bureau of Standards Eastern Automatic Computer’, Joint AIEE-IRE Computer Conference. Review of Electronic Digital Computers, Philadelphia 1951.

[9] Derrick Lehmer, ‘On the factors of 2^n +/-1’, *Bulletin of the American Mathematical Society*, vol. 53, 1947, 164-167. Lehmer computed the prime numbers on the ENIAC.

accounting in administrations, banks, insurance companies and public utilities.[10] An example of this is the computing of consumption times unit price, and billing in public utilities for thousands of customers. Analogue computers could not solve these problems. Digital computers were used to solve sets of linear equations and sets of differential equations. Unlike the universal usage of digital computers, electronic analogue computers' use was restricted to solving sets of differential equations, a field to which they were well-suited and that is most important in science and engineering, for example the Navier–Stokes equations in fluid dynamics which are applied in wind tunnel experiments. Also, the generation of random numbers and the application of Monte–Carlo–Methods were only possible on digital machines but not on analogue ones.[11] The following table summarises how analogue and digital computers could be applied on different fields of computing problems.

	Digital Computer	**Analogue Computer**
Calculation of an arithmetic formula	yes	no
Calculation of large prime numbers	yes	no
Maintain an account of an assurance or bank	yes	no
Administer a warehouse of spare parts	yes	no
Matrix calculations	yes	no
Monte Carlo Methods	yes	no
Solve a set of linear equations	yes	no
Solve a set of differential equations	**yes**	**yes**
Simulation in real time	**Not before 1980**	**yes**

Table 1: Different fields of computing problems.[12]

If here the digital high-speed computer is indicated as suitable for performing the Monte Carlo simulation, it should also be noted that the first simulation experiments with the Monte Carlo

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[10] Thomas Haigh, 'The Chromium–Plated Tabulator: Institutionalizing an Electronic Revolution, 1954–1958', *Annales in the History of Computing*, 23 (2001), issue 4, 75–104. Donald Eckdahl, Irving Reed, Hrant Sarkissian, 'West Coast Contributions to the Development of the General-Purpose Computer. Building Maddida and the Founding of Computer Research Corporation', in: IEEE Annals of the History of Computing, 2003, no. 1, 4–33, here 27, give an example for the application of the CRC 107 digital computer for the administration of spare parts of the US Air Force.

[11] Ceruzzi, *Beyond the Limits,* (cf. note 2), 138. Granino Korn/Theresa Korn, *Electronic Analog Computers*, second edition, New York 1956 mention on page 147 also Linear Programming as field of application of analogue computers, but this is the only source for this kind of application. For the Monte–Carlo–methods see Peter Galison, 'Computer Simulation and the Trading Zone', in: Gabriele Gramelsberger (ed.), *From Science to Computational Science,* Zurich 2011. Ulmann, *Analog Computing,* (cf. note 7), 179, reports on hybrid computers (cf. section 3.5) where the digital unit supplys the random numbers and the analogue one the computation.

[12] Cf. also Wolfgang Giloi and Rudolf Lauber, *Analogrechnen*, Berlin 1963, 3. The advantages of digital computers over the analogue machine are discussed by E. King and R. Gelman, 'Experience with Hybrid Computation', in *Proceedings of the Joint Fall Computer Conference,* Philadelphia 1962, 38.

method were performed with standard IBM punch card equipment such as the IBM 602, 603, and 604 punching calculators, and the generation of equally distributed random numbers for use in the Monte Carlo method was not performed with the digital high-speed computer. These statements can be derived from the results of the first symposium on the Monte Carlo method in 1949.[13]

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[13] Proceedings of a Symposium held June 29, 30, and July, 1, 1949, in Los Angeles, US Government Printing Office, Washington D.C. 1951

2 New Aeronautical Weapons after 1945

Already before the end of WW2, the West Coast of the United States developed a strong cluster of aeronautical industry. Around Los Angeles, one could find the firms Douglas Aircraft, Hughes Aircraft, Lockheed Aircraft, American Aviation, Consolidated Vultee (later Convair Aircraft) and Northrop Aircraft, with plants for final assembly and laboratories for R&D. The Boeing company was located in Seattle. The Lockheed assembly plant in Burbank produced during WW2 about 10.000 P–38 Lightning fighter airplanes with a workforce of 28.000 people in a 2–shift system during WW2.[14] A statistical analysis showed that the cluster surrounding Los Angeles was the greatest one in the US, and contributed to aircraft production five times greater than the second largest cluster.[15] A large Boeing assembly plant in Wichita, Kansas produced several hundred B–29 bombers.[16]

After WW2, the aeronautical industry increased in momentum through numerous government contracts to develop completely new types of weapons: fighter and bomber airplanes with jet propulsion, and anti-aircraft, battlefield, ballistic and guided missiles. All three branches of the armed services, the Army, the Air Force (since 1947) and the Navy funded independently without coordination contracts for the new types of aeronautical weapons.[17] Not only in the cluster around Los Angeles but all over the US, new sites for development laboratories were founded by all three branches of the armed services. For example, the Air Force maintained a lab in Cambridge, Massachusetts. The research group of Wernher von Braun, who came over from Germany with the Paperclip program, developed the German V2 rocket further in the Army's testing ground at White Sands in New Mexico that later was transferred to the Redstone Arsenal in Huntsville, Alabama, where it formed the Army Ballistic Missile Agency (ABMA).

While fighter planes were propelled by piston engines until 1944, the aeronautical industry received three government contracts to develop the new jet fighter planes. North American Aviation produced the fighter F–86, which flew for the first time in 1947, and Lockheed's P-80 Shooting Star had flown as

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[14] Sherman Mullin, *Robert E. Gross and the Rise of Lockheed: The creative Tension between Engineering and Finance*, in: Peter Westwick, *Blue Sky Metropolis – The Aerospace Century in Southern California*, University of California Press, Berkeley 2012, 57-78, here 64.

[15] Florencia Garcia-Vicente, Daniel D. Garcia-Swartz, Martin Campbell-Kelly, 'The History, Geography, and Economics of America's Early Computer Clusters', *Information and Culture*, issue 4, 2016, 445-478. Dana Parker, *Building Victory: Aircraft Manufacturing in the Los Angeles Area in World War II*, Cypress, CA, 2013.

[16] An overview on the locations of airplane production in the US during WW2 is given by Armen Alchian, 'Reliability of Progress Curves in Airframe Production', Econometrica, Vol. 31, No. 4 (Oct., 1963), 679-693.

[17] Small, *Analogue Alternative*, (cf. note 3), 88.

a prototype in 1944. The Republic Aviation Company in Farmingdale, New York, designed the F-84 Thunderjet, which flew as a prototype in 1946.[18]

Figure 2: Fighter Plane F–86

(Source: https://media.defense.gov/2004/Mar/15/2000593829/-1/-1/0/040315-F-9999G-010.JPG)

Also, the bomber fleet was changed to jet propulsion. The long range B–47 bomber with jet propulsion entered service in 1951. To build jet fighters and jet bombers required R&D at the supplier stage in order to produce jet engines.[19] For the long range B–52 bomber Pratt&Whitney, based in East Hartford, Connecticut, developed the J57 jet engine with 10,000 pounds of thrust , which reached the production stage in 1953.[20] The following figure shows the jet engine J57.

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[18] Laurence Loftin, *Quest of Performance. The Evolution of Modern Aircraft*, NASA 1985, Washington, D.C., 277. Mark Lovell and Hugh Levaux, *The Cutting Edge. Half a Century of U.S. Fighter Aircraft R&D*, RAND Corporation 1998.

[19] For the first flight of an US American jet fighter plane in 1942 see Hermione Giffard, *Making Jet Engines in World War II: Britain, Germany, and the United States*, Chicago: The University of Chicago Press, 2016, 37. Loftin, Quest, (cf. note 17), 223.

[20] National Museum of the US Air Force, https://www.nationalmuseum.af.mil/Visit/Museum-Exhibits/Fact-Sheets/Display/Article/195792/pratt-whitney-j57-turbojet/

Figure 3: A Pratt & Whitney J57 engine at the National Museum of the U.S. Air Force, Dayton, Ohio.

Like designing airplanes, the development of jet engines required a large amount of engineering work based on test runs and a long series of computational steps. These computations were carried out by a large workforce of male engineers and assisting female computers.[21] The large amount of engineering work can be seen in the DC–6 aircraft. It was estimated that the development of the military version of the aircraft, that entered service in 1946, required 1.3 million hours of engineering work at the Douglas Aircraft Company.[22]

Besides aircrafts also helicopters entered military service since 1944. In this year Igor Sikorsky built his model R–4 and in 1951 the first helicopter started that was powered by a turbine engine, the K–225 designed by Charles Kaman. In the late 1950s the helicopters were developed further to combat machines.

After 1945, several rocket programs were started. By 1947, the Air Force pushed 28 rocket programs, as the rocket historian Christopher Gainor noted. Allan Scott observed an "extraordinary extensiveness of rocket and missile development in Southern California", and summarized this development as follows.[23] On the basis of his earlier experiences in rocketry, Douglas undertook the

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[21] Jennifer Light, 'When Computers were Women', *Technology and Culture*, vol. 40, No. 3, 1999, 455-483. Ceruzzi, Limits (cf. note 2), 33. Richard Sprague, 'A Western View of Computer History', *Communications ACM*, 15 (1972), no. 7, 687. Beverly Columba, *Human Computers: The Women in Aeronautical Research*, dissertation 1994, in the web under https://crgis.ndc.nasa.gov/crgis/images/c/c7/Golemba.pdf. For the social history of female computing at the NACA aircraft research centre Langley see Margot Shetterly, *Hidden figures: The untold story of the African American women who helped win the space race*, London 2017. Sarah McLennan and Mary Gainer, 'When the Computer Wore a Skirt: Langley's Computers, 1935–1970', NASA History Program Office News & Notes Newsletter, vol. 29, No. 1, 2012, 25–32. Campbell–Kelly/Aspray, *Computer* (cf. note 1), 68s.

[22] Charles Strang, 'Computing Machines in Aircraft Engineering', *Joint AIEE-IRE Computer Conference. Review of Electronic Digital Computers*, Philadelphia 1951, 95.

[23] Gainor, *Atlas* (cf. note 28), 351. Allen Scott, 'The aerospace-electronics industrial complex of Southern California: The formative years, 1940-1960', *Research Policy* 20 (1991), 439-456, here 442. For the rocket development see also Bill Gunston, *The Illustrated Encyclopedia of the World's Rockets and Missiles*, London 1979.

production of the Nike Ajax surface-to-air missile in 1945 and the Sparrow II in 1950. In 1947, Hughes Aircraft had an Air Force contract for guided air-to-air missile development, which resulted in the Falcon missile of the early 1950s. In 1945, Consolidated Vultee initiated an R&D program that would eventually lead to the Atlas intercontinental ballistic missile. Also in 1945, Consolidated Vultee produced the Lark surface-to-air missile and Ryan Aeronautical began work on the Firebird. Boeing started in 1946 on an anti aircraft missile project that later became known as Bomarc. It relied on the Semi-Automatic Ground Environment (SAGE), an automated control system for detecting, tracking and intercepting enemy bomber aircraft. Its warhead could be equipped with a 10 kiloton atomic bomb. The fiscal year 1953 saw the Department of Defense (DoD) for the first time spend more than $1 million on missile research, development. and procurement.[24]

Figure 4: The anti aircraft rocket Falcon

(Source: USAF/White Sands Missile Range Museum)

Since the German flying bomb V1 was known about in 1944, the US military was eager to build similar items and develop them further to winged guided missiles.[25] These were seen as a pilotless bombers and became an important issue in all three branches of the armed forces.[26] The Navy gave a contract to North American Aviation to develop the guided missile Navaho. The Air Force ran the Strategic Missile Program SM 62 from 1945 to 1961 and had already asked for a pilotless bomber in 1945. At the same time, Northrop Aircraft had an Air Force contract MX775 to develop a long range subsonic guided missile with jet propulsion (the Snark missile).[27] It possessed an ambitious guidance

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[24] Roger Bilstein, *A History of the NACA and NASA, 1915 – 1990*, Washington, D.C., 1998, 43.

25 Gunston, (cf. note 22), 33.

26 Small, (cf. note 3).

27 Kenneth Werrell, *The Evolution of the Cruise Missile*, Air University Press, 1985.

system with an analogue computer that defined the route to be flown and was corrected by star tracking.[28]

Figure 5: Snark Missile (Source: https://missilethreat.csis.org/missile/snark/)

Northrop made hundreds of test flights before the Snark missile, endowed with a four megaton hydrogen bomb, entered service for nuclear deterrence from 1958 until 1961, when it was replaced by the Atlas intercontinental ballistic missile (ICBM).[29] Before global positioning systems became operational in 1985, neither Snark nor Atlas could not navigate over long distances to the target as precisely as a bomber that was governed by pilots. The deviation from the target could be anywhere from 10 to 50 miles.[30] This lack of precision was substituted by the high load of a four megaton hydrogen bomb, whereas a B–29 bomber destroyed Hiroshima with just a 13 kiloton atomic bomb in August 1945, when the bomb was dropped on the city. The difficulties in developing a long-range guided missile can be guessed by the period of 13 years from 1945 to 1958 spent on development.

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[28] Sprague, (cf. note 20). National Museum of the US Air Force https://www.nationalmuseum.af.mil/Visit/Museum-Exhibits/Fact-Sheets/Display/Article/196745/northrop-sm-62-snark/. For star tracking navigation see Arthur Locke, *Principles of Guided Missiles Design – Guidance*, New York 1955, chapter 15–6. The hydrogene bomb (“super”) was discussed among scientists since 1942, see Rhodes, Atomic bomb, (cf. note 73), 418–421.

[29] Christopher Gainor, ‘The Atlas and the Air Force: Reassessing the Beginnings of America's First Intercontinental Ballistic Missile’, *Technology and Culture*, Volume 54, Number 2, April 2013, 346-370. Jacob Neufeld, *The Development of Ballistic Missiles in the United States Air Force, 1945-1960*, Washington, D.C., 1990. Edmund Beard, *Developing the ICBM: A Study in Bureaucratic Politics*, Columbia University Press, 1976.

[30] Locke, *Guidance*, (cf. note 27), 302. For the debate of accuracy of nuclear missiles see Donald Mackenzie, *Inventing Accuracy – A Historical Sociology of Nuclear Missile Guidance*, Cambridge (Mass.), 1990. Gainor, Atlas (cf. note 28), 359.

The Air Force stopped the project Navaho in 1958. In the 1950s Convair Aircraft got an Air Force contract for the ICMB Atlas.[31] Convair built a factory in the region of San Diego for the production the Atlas. This rocket consisted of 100,000 parts that were delivered to the factory by a supplier network consisting of 3,500 suppliers (see below).[32]

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[31] Small, *Analogue Alternative* (cf. note 3), 147 – 152. For the project Atlas see Gainor, Atlas (cf. note 28).

[32] Gunston, *Illustrated Encyclopedia* (cf. note 22), 62.

3 Designing and Computing Airplanes and Missiles

This section describes fields of application for analogue and digital computers in the aeronautical industry. This includes the behaviour of airframes in the air as “dynamical systems”, the simulation of guided missiles and the support in the design of airframes. The guidance systems of ballistic missiles are omitted here, but could also be explored.[33] Already, several observers have stated the links between the aeronautical and computing industries. The progress of one stimulated the other one. The success stories of the development of high speed digital computers on the East Coast completely omit the new aeronautical weapons as drivers for advanced computing devices.

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[33] On the simulation of the guidance system of the missile V2 see James Tomayko, ‘Helmut Hoelzer’s Fully Electronic Analog Computer’, *IEEE Annales of the History of Computer*, Vol. 7, No. 3, July 1985, 227–240.

3.1 Airframes as dynamical systems

The boom of orders for new aeronautical weapons resulted in a great pressure on the design departments of the aeronautical firms. How could they respond to this pressure? All the different weapons require similar methods of describing the weapons' movements in the air, as a "dynamical system". This could be accomplished by a set of simultaneous differential equations that describe the forces of acceleration acting on the airframes of the flying weapons and governing their directions in three dimensions.[34] The following figure shows an airplane in a study of pitching characteristics, in which the elevators are manipulated.

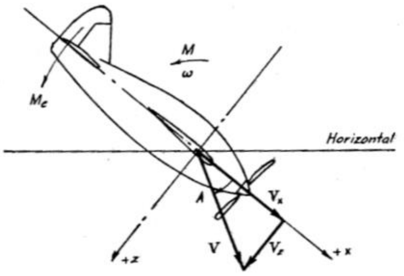

Figure 6: Movement of an airplane.[35]

The behaviour of the airplane can be described by three differential equations, which define the increments in downward, forward and angular velocities that could be solved by a mechanical analogue computer or an electronic analogue computer.[36] The equations read as follows:

$$(p + k_{xx})v_x + V_o(\sin A_o)\omega + g(\cos \theta_o)\frac{\omega}{p} = k_{xz}v_z \qquad (19)$$

$$-(p + k_{zz})v_z + V_o(\cos A_o)\omega - k_z w^W + g(-\sin \theta_0)\frac{\omega}{p} = k_{zx}v_x \qquad (20)$$

$$-(k_{Mz}p + k_{Mz})v_z + k_{Mx}v_x + \frac{M_e}{J} = (p + k_{M\omega})\omega \qquad (21)$$

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[34] Richard Sprague, (cf. note 20), 688.

[35] John Raganzzini, Robert Randall and Frederick Russel, 'Analysis of Problems in Dynamics by Electronic Circuits', *Proceedings of the I.R.E*, May 1947, 444–452, here 449.

[36] Ibidem. For the flight equations see also Granino Korn/Theresa Korn, *Electronic Analog (*cf. note 10), 116.

3.2 The invention of the electronic analogue computer

Analogue computing techniques by electrical–mechanical meanes have been known since the 1920s, when problems of stability in power grids were considered, and special purpose computing machines were built, also as fire command systems for military purposes. In the 1930s, Vannevar Bush opened a lab at MIT with a mechanical analogue computer – also called a differential analyser – and offered it for computing projects to solve a set of differential equations, at a cost of 400$ per hour of use.

The electronic analogue computer based on the DC–amplifier that amplified in a ratio of 1:100000 and was driven by electronic tubes and developed in the 1940s by the Bell Labs in New York City.[37] On the DC–amplifier based a special purpose electronic analogue computer – also developed by Bell Labs – for the director of anti aircraft gun T10 that was supported by radar techniques.[38] The literature reports on the very successful application of the T10 with radar as an automatic firing system, used to shoot down V1 flying bombs over London and Antwerp. David Mindell called the V1 battles over London and Antwerp the first robot battles in history.[39] After 1945, it was recognized that Bell's special purpose electronic analogue computer could be transformed into a general purpose electronic analogue computer to solve various sets of differential equations. This kind of computer was also called electronic differential analyser which could compute additions, differentiations in functions and the integration of functions and programmed by various links on the plugboard. The following figure shows how to build the circuits around the DC–amplifier for those operations.[40]

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[37] E. Ginzton, 'DC amplifier techniques', *Electronics*, March 1944, 98–102.

[38] Aristotle Tympas, 'A Deep Tradition of Computing Technology: Calculating Electrification in the American West', in: *Where Minds and Matters Meet: Technology in California and the West*, Volker Janssen (ed.), University of California Press, Oakland, CA, 2012, 71-101. David Mindell, 'Automation's finest Hour: Bell Lab and the Automatic Control in World War II', *IEEE Control Systems*, December 1995, 72–80. M. Fagen (ed.)*, A history of engineering and science in the Bell system. National service in war and peace (1925 - 1975)*, Bell Laboratories, New York, 1978, 139. Ulmann, *Analog Computer* (cf. note 7), 56.

[39] Mindel, Automation's, (cf. note 38), 77. Small, *Alternative* (cf. note 3), 69.

[40] Granino Korn/Theresa Korn, *Electronic Analog Computers*, New York 1952, 11. A second edition appeared 1956. Small, *Alternative*, (cf. note 3), 74.

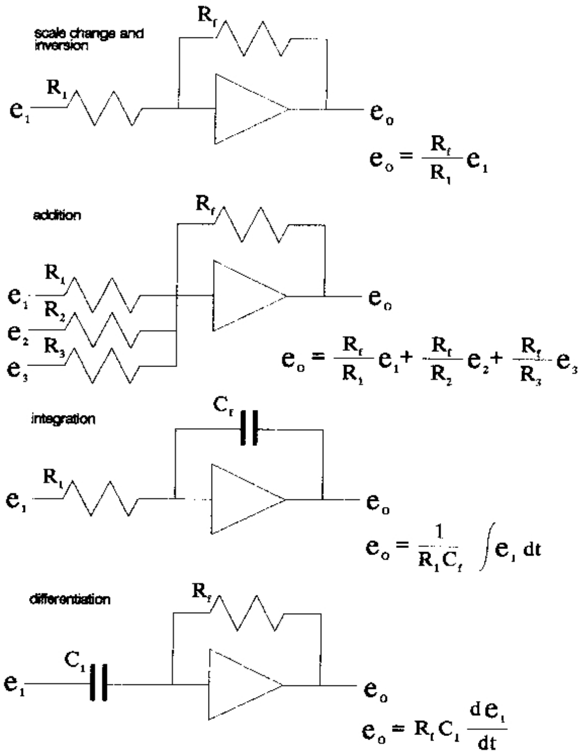

Figure 7: Circuits with the DC–amplifier to conduct mathematical operations.

3.3 The boom of electronic analogue computing induced by ONR

With their projects for guided missiles, military agencies induced a boom of electronic analogue computing machines. The Office of Naval Research (ONR) started the project Cyclone in 1946 with the firm Reeves Instruments, based in New York City. The aim of Cyclone was to build a machine to simulate the flight of guided missiles.[41] This simulation was an important issue insofar as test flights ended in the destruction of the missile, because it had no device for landing. Northrop built a landing zone in Cape Canaveral for its Snake missile project to recover the airframes. The difficulty of controlling the missiles during test flights was shown when one Snake missile escaped erroneously to Brazil. Simulations would save money and time, and no replacement for a destroyed missile would be necessary. The IBM engineers Sheldon and Tatum described the difficulties of obtaining test data during the test flight of a guided missile: “Tracking it on a test range was the only way to make sure of its performance. At one test facility, this was done by planting camera batteries or photo-theodolites along a 100-mile course. During its flight, the missile position was recorded by each camera at 100 frames per second, together with the camera training angles. Before the digital IBM calculator 604 would be employed, the thousands of pictures from each camera were turned over to a crew of female computers, to determine just what had happened. It took two weeks to make the calculations for a single flight.”[42]

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[41] James Small, General Purpose (cf. note 3).

[42] John Sheldon and Liston Tatum, ‘The IBM Card-Programmed Electron Calculator’, *AIEE-IRE '51 Papers and discussions presented at the Dec. 10-12, 1951, joint AIEE-IRE computer conference: Review of electronic digital computers*, 30. Reprinted in Brian Randell’s collection, *The origins of digital Computers*, Berlin 1973. On the recording of test flights of manned aircrafts and the evaluation of the records by female computers see Frederick Suppe, ‘The Changing Nature of Flight and Ground Test Instrumentation and Data: 1940–1969’, in: Peter Galison and Alex Roland (eds.), *Atmospheric Flight in the Twentieth Century*, Dordrecht u.a.: Kluwer Acad. Publ., 2000, 67–106, here 75.

In the Cyclone project, the firm Reeves embarked on the Bell Lab's special purpose electronic analogue computer and became the first supplier for commercial electronic analogue computing devices in 1948. It was marketed very successfully under the name REAC. Three years after its market entrance, in 1950, there were already 60 REAC systems throughout the US, showing the high demand for computing solutions, presumably in the aeronautical industry. In New York City, the ONR organized a symposium for REAC–Techniques in 1951.[43]

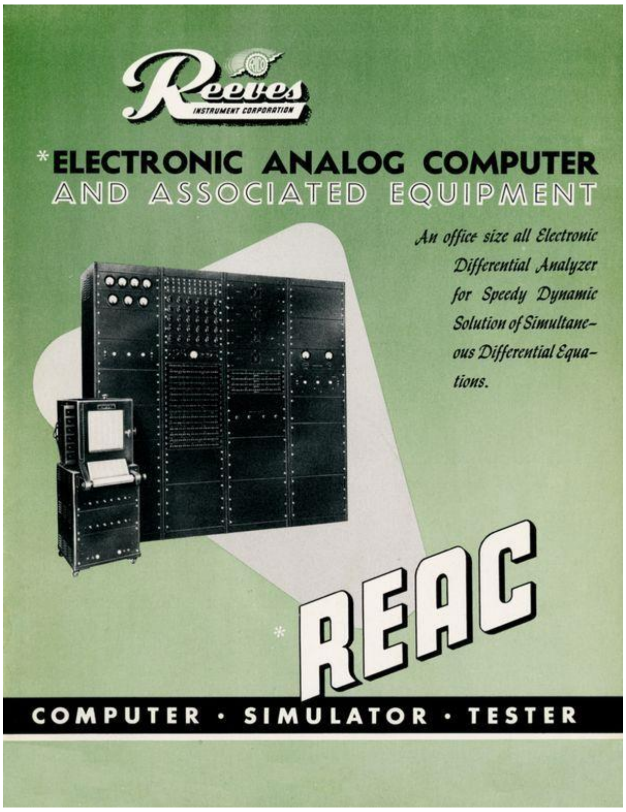

Figure 8: Advertisement of Reeves Instruments underlines the solution of differential equations 1950, speedy solutions and the office size of the machine.
(Source: Computer History Museum in Mountain View, http://www.computerhistory.org/revolution/analog-computers/3/150)

In 1947, following up on Cyclone, the ONR contracted the Typhoon project with the Radio Corporation of America (RCA) lab in Princeton, New Jersey – in the neighbourhood of the Institute for Advanced Study (IAS), where John von Neumann worked – which had also the aim for simulating guided missiles and developing anti aircraft missiles.[44] Besides the policy to directly fund the development of electronic analogue computers, the military agencies gave contracts for airframes to aeronautical firms with sufficient financial volume to develop electronic analogue computers

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[43] F. Bauer, L. Brock, P. Manfredi, B. Meissinger, H. Sherman, (eds.), *Symposium 1 on REAC techniques, March 15-16*, New York 1951.

[44] For the projects Cyclone and Typhoon see James Small, General Purpose (cf. note 3).

themselves, to conduct their designing tasks for airframes. In addition to Reeves Instruments, Goodyear Aircraft, Boeing Aircraft, Electronic Associates (West Long Branch, New Jersey), Northrop Aircraft, Beckman Instruments (Pasadena) and Philbrick appeared on the market, offering electronic analogue computers.[45] It is striking that with Boeing, Northrop and Goodyear Aircraft, three aeronautical firms entered the electronic analogue computer market, because in this industry, the design process in aircraft and missile projects relied heavily on the solution of sets of differential equations. Goodyear Aircraft began to manufacture the GEDA (Goodyear Electronic Differential Analyser) in 1949.[46] Boeing's computer was marketed under the name BEAC (Boeing Electronic Analog Computer) and entered the market in 1950, see figure 1. Boeing developed the computer in connection with the GAPA anti aircraft missile project.[47]

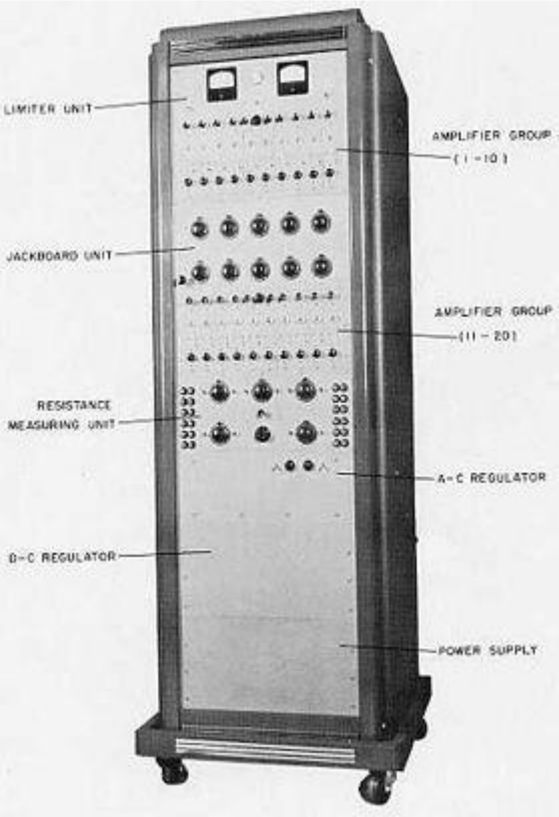

Figure 9: Analogue Computer of Goodyear 1951 (GEDA).

(Source: Goodyear Analog Museum www.cowardstereoview.com/analog/good.htm)

Some aeronautical firms developed with the large funds of US military electronic analogue computers for their needs but did not offer them as commercial products. The Wright Aeronautic Corporation – one of the major producer of aircraft engines – built an electronic analogue computer to support the

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45 Small, General Purpose (cf. note 3), 12.
46 Small, *Analogue Alternative*, (cf. note 3), 101s.
[47] Ibidem.

design of a turboprop engine in 1946. The following figure shows the elements of a turboprop engine.

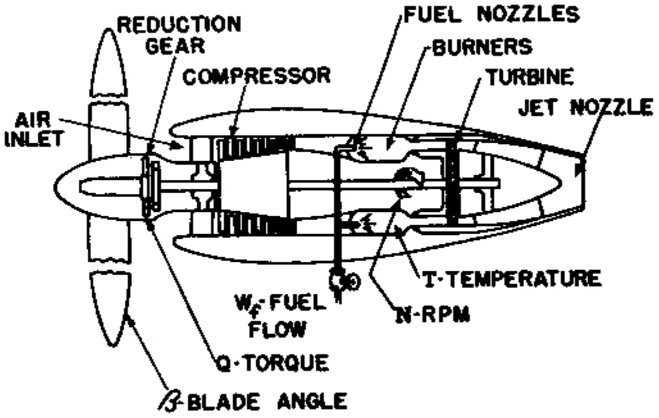
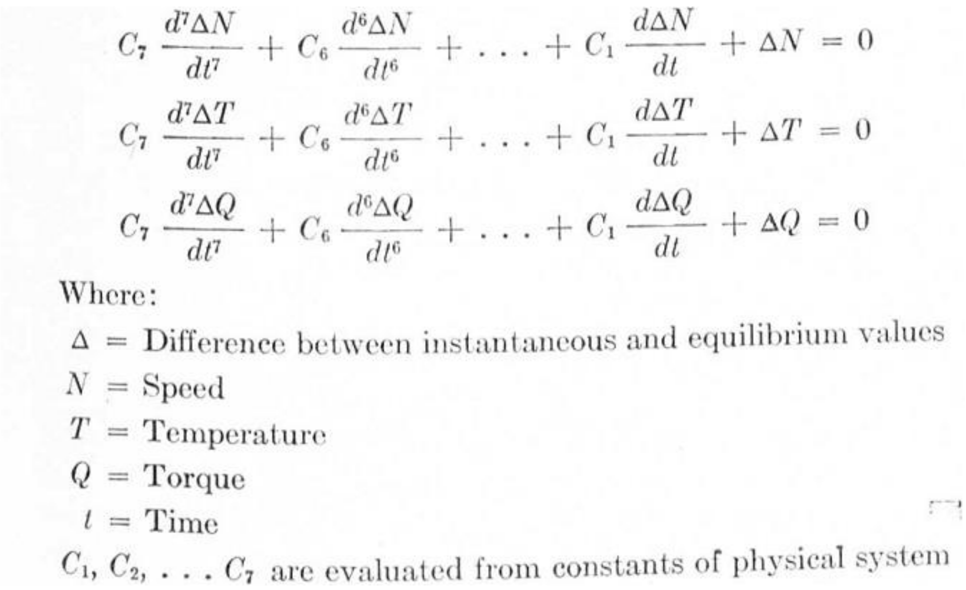


Figure 10: Schematic diagram of a typical turboprop engine (Philbrick et al., p. 234)

According to Wright Aeronautic Corporation, in a model five variables and control loops will demonstrate how a change in fuel will produce a change in speed, torque, and temperature. Also, the change in propeller blade angle will induce changes in speed, torque, and temperature. The model can be written as a differential equation of order seven:[48]



$$C_7 \frac{d^7\Delta N}{dt^7} + C_6 \frac{d^6\Delta N}{dt^6} + \ldots + C_1 \frac{d\Delta N}{dt} + \Delta N = 0$$

$$C_7 \frac{d^7\Delta T}{dt^7} + C_6 \frac{d^6\Delta T}{dt^6} + \ldots + C_1 \frac{d\Delta T}{dt} + \Delta T = 0$$

$$C_7 \frac{d^7\Delta Q}{dt^7} + C_6 \frac{d^6\Delta Q}{dt^6} + \ldots + C_1 \frac{d\Delta Q}{dt} + \Delta Q = 0$$

Where:

Δ = Difference between instantaneous and equilibrium values
N = Speed
T = Temperature
Q = Torque
t = Time
$C_1, C_2, \ldots C_7$ are evaluated from constants of physical system

Although as many as 25 design characteristics may be involved in the engine's control system, the analogue computer could determine the optimum values for them over the course of a single day.[49] The following figure shows the WAC electronic analogue computer.

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[48] C. Philbrick, W. Stark and W. Schaffer, 'Electronic Analog Studies for Turboprop Control systems', *SAE Quarterly Transactions*, April 1948, Vol. 2, No. 2, 234–241, here 238 (available in Paynter, Palimpsest, cf. note 6). SAE is the abbreviation of Society of Automotive Engineers. The paper was presented at the SAE National Aeronautic Meeting in Los Angeles on 3 October 1947.

[49] Ibidem.

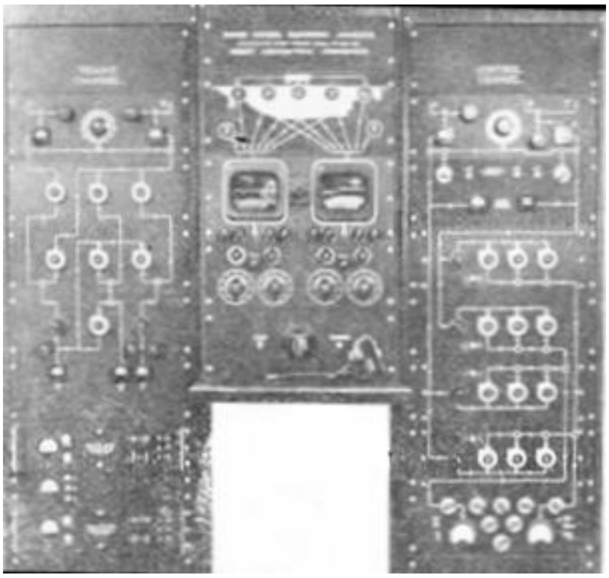

Figure 11: Electronic Analogue Computer of Wright Aeronautic Corporation 1946.[50]

The ONR's and other military agency's contracts induced a boom in computing devices that included the digital electronic calculator IBM 604 by 1948. When one reviews the journals on machine computing and physics of this time, they reveal a rich variety of computing machines for science and engineering. One finds a great number of analogue computers and many digital computers with a high speed arithmetic units (based on electronic tubes) but with a low speed access to the drum memory.[51] In 1950, the small engineering company ERA offered its computer model ERA 1101 to the aeronautical labs. This was the first digital computer that combined a high speed arithmetic unit with a low speed magnetic drum memory. The drum was the first reliable digital memory. The von Neumann architecture could be applied to this machine, and the data and program could be loaded onto different sectors of the drum. ERA became a major computer supplier to the Army.[52] An example of the emergence of analogue computers is the Consolidated Engineering Corporation in Pasadena, CA, that built an analogue computer to solve system linear equations up to 12 variables in 1945. It later built the "Datatron" digital computer in 16 copies.[53] The boom in computing devices was accompanied by many publications and conferences on digital and analogue computing. In 1955, Henry Paynter edited a collection of reprints of papers on electronic analogue computers which was

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[50] Ibidem, 237.

51 I draw on the journal *Mathematical Tables and other Aids of Computation*, sections News and Bibliography.

52 Erwin Tomash and Arnold A. Cohen, 'The Birth of an ERA. Engineering Research Associates Inc., 1945-1955', *IEEE Annals of the History of Computing*, vol. 1, 1979, no. 2, 83-97, here 95. For the development of the magnetic drum memory see Charles Bashe, Lyle Johnson, John Palmer, Emerson Pugh, *IBM's Early Computers*, MIT Press 1986, 77 and session four of *Proceedings of a Symposium on Large-scale Digital Calculating Machines*, Harvard University 1947.

53 Clifford Berry, Doyle Wilcox, Sibyl Rock and H. Washburn, 'A computer for solving linear simultaneous equations', *Journal of Applied Physics*, vol. 17, Apr. 1946, 262-272. Martin Weik, *A Survey of Domestic Electronic Computer Systems, report no. 971, Aberdeen 1955*. ERA (ed.), *High Speed Computing Devices*, McGraw-Hill, New York 1950. 21.

widely accepted and distributed. In 1965, a forth print appeared. In 1952 the first book on analogue computing machines appeared, which had a second print in 1956.[54]

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[54] Paynter, Palimpsest, (cf. note 6). Joint Western Computer Conference, Los Angeles 1951 and 1953. Korn/Korn, (cf. note 11).

3.4 The design process of air frames

The simulation of a guided missile's flight and the design process of airframes required much computational work. According to the assessment of Douglas Aircraft manager Charles Strang, much of the work done during the formative stages of airframe design is only tentative. It is subject to change and deprived of its final status until a large and growing volume of calculations can be performed. If that work proceeded on a more solid basis, much wasted engineering time could be avoided.[55] Here, a real saving is accomplished when the work of hundreds of engineering personnel can be supported by computers. The structural analysis of airframes also afforded much engineering work and computations. As the Lockheed engineers Mazelsky and O'Connell pointed out, aeroelastic problems occur in airframes such as flutter, airplane dynamic stability as affected by wing and tail elasticity, gust loads, and vibration problems involved in landing and taxi load investigations.[56] Therefore, engineers in aeronautical firms saw electronic analogue computers as important tools for support. Sets of differential equations could be solved and simulation studies carried out. There were no alternatives for solving sets of differential equations other than visiting MIT and using the mechanical differential analyser for 400$ per hour, or the mechanical differential analyser at General Electric in Los Angeles. High speed digital computers were not available, since IBM only entered the market with IBM 701 mainframe computers as late as 1953. The mainframe Univac 1 from Remington Rand was available in 1951 but was focused towards public and business administration. The first Univac 1 was delivered to the census. In 1953, Univac offered its scientific digital computer 1103.

In the sources given, one can find further examples of employing analogue computing during the airframe design process. At Lockheed, aircraft engineers simulated the behaviour of landing gears and solved equations for the hydraulic orifice force, the gas pressure force, the shock stunt friction force and the foe and aft drag force on a Boeing Electronic Analogue Computer. This provided a means of overcoming landing gear mathematics.[57] The landing gear differential equations were given as follows:

$$
\begin{aligned}
&F \sin\theta + SK_2 \cos\theta + M_2 \ddot{h} - P_D + K_3 \dot{h} = 0 \\
&K_1 v + M_2 \ddot{v} + SK_2 \sin\theta - F\cos\theta = 0 \\
&M_1 \ddot{x} + F\cos\theta - (1-L)W = 0
\end{aligned}
$$

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[55] Strang (cf. note 21), 95.

[56] B. Mazelsky and R. O'Connel, 'The Integrated Use of Analog and Digital Computing Machines for Aircraft Dynamic Load Problems', *Joint AIEE-IRE Western Computer Conference 1955*, Los Angeles, 66–68.

[57] D. Drake and H. Foster, 'Airplane Landing Gear – Performance Solutions with an Electronic Analog Computer', in: *AIEE Joint Computer Conference*, Los Angeles 1953, 86-97.

Figure 12: Landing Gear of Lockheed P–38 (Press Release Lockheed)

Another example is flutter analysis, in which aircraft wings begin to flutter at critical speeds and has been known about since the 1920s. The mathematical formulas for describing the flutter phenomenon are complex and could only be solved with the aid of a computer. The traditional procedure, without the aid of a computer, would have needed the design to be completed, the prototype airplane be built, and natural frequencies and modes determined by the forced vibration of the prototype. Months of calculations based on this data would then have to be carried out.[58] Instead, Douglas Aircraft used the simulation of flutter of wings on the electronic analogue computer that the California Institute of Technology in Pasadena, CA built in 1947, together with the Westinghouse Electric Corporation. This machine could solve partial differential equations up to three variables. The machine worked within the error margin of 1% to 5%, which was understood to be sufficient for most engineering tasks. The partial differential equation for flutter analysis looked as follows:[59]

$$\frac{\partial}{\partial x}\left[GJ\,\frac{\partial \alpha}{\partial x}\right] \pm S_{\alpha}\frac{\partial^{2} y}{\partial \tau^{2}} + I_{\alpha}\frac{\partial^{2} \alpha}{\partial \tau^{2}} = -\Pi\rho\,\frac{b^{3}(x)}{2}\,\frac{\partial^{2} y}{\partial t^{2}} - \Pi\rho\,\frac{b^{4}(x)3}{8}\,\frac{\partial^{2} \alpha}{\partial t^{2}} - \Pi\rho V\,b^{3}(y)\,\frac{\partial \alpha}{\partial t} + g(x,t)$$

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[58] Mazelsky/O'Connel, (cf. note 55).

[59] E.L. Harder and G.D. McCann, 'A Large Scale General Purpose Electric Analog Computer', *AIEE Transactions*, vol. 67, 1948, 664-73. Charles Strang, (cf. note 21), 97. For other examples of flutter analysis see the Simulation Council Newsletter, in *Instruments and Automation*, 1957, 1519.

3.5 Features of electronic analogue computers as engineering tools

IBM offered simple digital computers 604 since 1948 and CPC since 1949 (cf. sections 3.7 and 4.2). These machines were not really suitable for solving sets of differential equations.[60] Therefore, the engineers adapted enthusiastically to the electronic analogue computers that could carry out this task very well. In the literature, there are many sources reporting on how analogue computers convey a “feeling” for the dynamic system to the engineers. In addition, they give engineers a deeper insight into these systems.[61] These machines were cheap and available locally, in the lab. A basic unit could be bought for $ 8000 – the equivalent of two years salary for an engineer. An advanced model with complementary devices cost $ 16.000.[62] A striking feature of electronic analogue computers was their speed solving ordinary differential equations that depend only on the one variable time. In his book on analogue computing, James Small had already contextualized the contemporary debate on computing speed.[63] Therefore, I can only give a short overview. A set of ordinary differential equations could be solved within one minute by analogue machines. As comparisons in the years 1954 and 1955 showed, high speed digital computers needed one hour for a solution, because they operated strictly sequentially in the von Neumann architecture. The euphoric expectations surrounding the possibilities of high speed digital computers were, therefore, disappointed.[64] In her study on simulation experiments, Gabriele Gramelsberger points out that John von Neumann has very high hopes for the digital wind tunnel, which would be operated with digital high-speed computers.[65]

Other than mathematicians, who lacked expierences in laboratories, engineers and scientists in the Cold War industrial R&D scenery linked their experiments to the need to record the data they produced in experiments, e.g. in wind tunnels. In a second step, after recording and reducing the data, arose the need to perform calculations with the data for which simple computing machines (analogue or digital) were sufficient. The Computer Research Corporation offered in 1951 their digital model CRC102 with von Neumann architecture and drum for 1023 words for data reduction and

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60 The IBM engineers John Sheldon and Liston Tatum report on the use of the CPC machine to solve differential equations, (cf. note 42).

61 Mazelsky/O’Connel, (cf. note 56), 67. W. Drake and H. Foster, ‘Airplane Landing Gear Performance. Solutions with an Electronic Analog Computer’, *Proceedings of the Western Computer Conference 1953*, 86–97, here 91. John McLeod, ‘Ten Years of Computer Simulation’, *IRE Transactions on Electronic Computers*, Februar 1962, 2–6, here 3.

62 Lee Cahn, ‘A New Concept in Analog Computers’, *Western Computer Conference*, Los Angeles 1953, 196–202.

63 Small, Analogue Alternative, (cf. note 3), 253.

64 Arthur Vance, ‘The Role of Analog and Digital Computers in Simulation’, *Proceedings of the Western Computer Conference*, held by the Joint IRE-AIEE-ACM Computer Conference Committee, Los Angeles, February 4-6, 1953, 24-27, here 26.

[65] Gabriele Gramelsberger, Computerexperimente, Zurich 2010, pp. 76–82.

simple calculations.[66] The company Royal McBee offered since 1955 a small portable digital computer LPC 30 with a drum of 4096 words, which was used to support engineering tasks. These included reduction of wind tunnel test data, missile development studies, jet engine test analysis, development of airfoill sections, stress and weight studies.[67]

From this kind of work flow the engineers and scientists did not derive a special need for high speed digital computers. On a mainframe digital computer, the calculations in the lab were cumbersome because the mainframe digital computer dealt with tapes as memory units instead of a drum. Reducing the test data, assembling each part of the program, and finally the main run were done one at a time, each requiring a tape change. The workflow required at least two hours.[68]

Instead of lining up in the computer centre's queue and waiting for computation service (the closed shop model), simple analogue computers had the characteristics of locally available lab computers. These characteristics supported their use for simulation studies. Initially, aircraft companies used external computing centres for analogue computing projects, but in 1949 they began to install analogue computers in their own labs, as Douglas Aircraft data shows. Before 1949, Douglas had used outside computer centres, such as the General Electric mechanical analyser in Los Angeles, the Thermal Analyser in Los Angeles, the Reeves Company, Project Typhoone, Project Cyclone and the analogue computer at the California Institute of Technology in Pasadena, California.[69]

Another feature of electronic analogue computers was their flexibility. The DC–amplifiers could be coupled to enhance performance and solve more equations. In the mechanical differential analyser at MIT, 18 integrators could be coupled. This was also possible with electronic analogue computers. But the seeming ease of analogue computing in fact led eventually to a dead end. The large installations with DC–amplifiers in the projects Typhoon and Cyclone became overly complex, and the reliability of the plug connections could not be controlled. In addition, setting up large computing systems took several months. The solution was the hybrid technique, where digital and analogue computers were coupled with interfaces. The digital computer played the role of supervising the setup and plug connections of the analogue. The simulation was carried out on the analogue machine. In the late

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[66] Akera, (cf. endnote 17), p. 242s. For the predecessor machine CRC 101 see *Digital Computer Newsletter*, vol. 3, 1951, no. 2, p. 4, Computer History Museum, Catalog Number 102640431.

[67] Royal McBee booklet on LPC30, source: Computer Museum Mountain View.

[68] S. Lanzarotta, "Computing Power at Huntsville", *Datamation*, July 1960, p. 18–21, here p. 20.

69 Strang, (cf. note 21), 95–96. Cahn, (cf. note 62), 198.

1950s, interfaces appeared on the market for the digital computers IBM 704 and Univac 1103A.[70] The hybrid technique was also used to improve the accuracy of computing results (see below).

In the contemporary debate regarding analogue computers, the issue of accuracy is important. In his book on analogue computing, James Small contextualized the debate on computing accuracy.[71] I can, therefore, only give a short overview and provide additional views. The mechanical integrator at MIT computed within a small error margin of 1%, because it was built using high precision tools. The first electronic analogue computers could compute in error margins between 1% and 5%. But this was seen as sufficient, because the data base in aeronautical design was only rough. There were many sources that report on a recalculation of results derived on electronic analogue machines on the digital IBM CPC machines, but no deviations were discovered. In the Typhoon project the computers improved the accuracy on 1 to 25,000. The proponents of digital computing brought about the issue of accuracy to denigrate the analogue technique. John von Neumann sent warnings about the lack of accuracy in analogue computing.[72] The digital technique could achieve an arbitrarily small margin of error by expanding the digits used for computing. This is, however, only a theoretical consideration. In practice, memory space was scarce, and no numbers with a large number of digits could be computed. The data base, meanwhile, in meteorology and atomic weapons – the main fields of John von Neumann's work – was coarse, so that high precision calculations were not indicated.[73] Before the advent of computers engineers and scientists – also John von Neumann – used rule of thumb to make an assessment on the results of a set of differential equations. On this procedure the claim of a lack of accuracy did not apply. Stanislaw Ulam reported on a rough assessment of the chain reaction at Los Alamos in the region of 10%.[74] The physicist Enrico Fermi started the first nuclear reactor at university of Chicago in 1942 with the computing aid of a slide rule that has an accuracy of about 1 percent.[75]

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70 Small, General Purpose (cf. note 3), 13.

71 Small, *Analogue Alternative*, (cf. note 3), 257. For the view on accuracy of the proponents of analogue computing see EAI, *Handbook* (cf. note 79), chapter 12.

72 Winter Meeting of the American Institute of Electrical Engineers in New York, January 1947, *Mathematical Tables and other Aids of Computation*, vol. 2, 1947, 368. Summer Meeting of the Mathematical Association of America, September 1947 in Yale, *Mathematical Tables and other Aids of Computation*, vol. 3, 1948, 58. In a discussion with Norbert Wiener John von Neumann refused to use an analogue computer, see Ulam, von Neumann (cf. note 70), 95.

73 Philip Thompson, ‘Weather Prediction’, in: Preston Hammer (ed.), *The Computing Laboratory in University, Madison 1957*, 27–42. Thompson refers to high speed computing for weather prediction at the IAS, but did not mention analogue computing to solve the differential equations.

[74] Stanislaw Ulam, ‘Von Neumann. The Interaction of Mathematic and Computing’, in: Nicholas Metropolis et al. (ed.), *A history of computing in the twentieth century: a collection of essays*, New York, Acad. Press, 1980, 93–99, here 96.

[75] Richard Rhodes: The Making of the atomic bomb, 1986, second edition 2012, p. 438.

The simulation of dynamic systems on high speed digital computers in the labs became possible – but not in real time – when, at the end of the 1950s, operating systems and the programming language FORTRAN became available. But programming in FORTRAN was tedious, because it required several steps:[76]

1) Writing the program in FORTRAN and punching cards carrying the FORTRAN program.
2) Loading a stack of punched cards with the FORTRAN compiler into the computer and running the compiler.
3) Loading a stack of punched cards with the FORTRAN program. The compiler produces a stack of punched cards with the machine instructions of the program. If the compiler indicates errors in the program code, then you must go back to step 1).
4) Loading a stack of punched cards with the machine instructions of the program into the computer, then running the program.
5) Loading a stack of punched cards with the data to be explored into the computer, then running the program. The computer will produce a stack of punched cards with the results, showing how the program operated on the data.

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[76] See Dale Fisk: Memories of a Fortran program writer, under http://www.columbia.edu/cu/computinghistory/fisk.pdf

3.6 Simulation in real time: The second and third boom in analogue computing

The high speed of electronic analogue computers allowed simulation studies, used as important tool for supporting engineers in the design process in aeronautical projects to study the behaviour of guided missiles (project Snark), ICBM rockets (project Atlas), rocket driven airplanes (project X15) and the launch of a man into the orbit (project Mercury) in real time.[77] Digital computers could not provide this speed to simulate in real time.[78] During the process of simulation, changing some parameters would allow the new solution to be completed quickly on the analogue machine. The output devices were XY–plotting machines which showed the resulting curves on paper and oscilloscope tubes, where the behaviour of dynamic systems and deviations from steady states could be observed. Installations of Land cameras shot photos of the screens for later analysis.[79] The following figure shows screen shots of the Wright Aeronautic Corporation electronic analogue computer in the design of turboprop engines.[80]

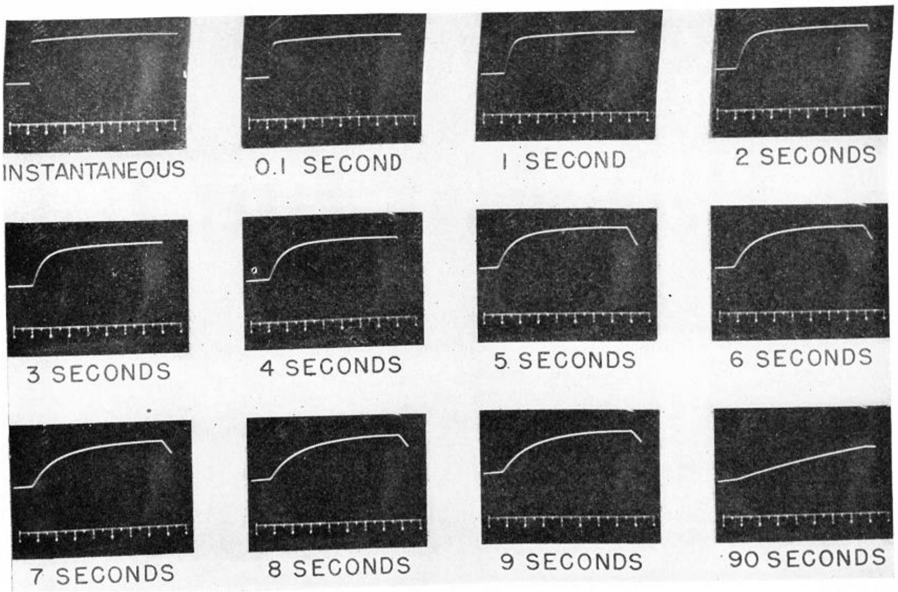

Figure 13: Screen Shots of the Wright Aeronautic Corporation Analogue Computer.

The ability to conduct simulation studies of dynamical systems in real time induced new booms in analogue computing and led to important institutionalizations. The major players in the West Coast aeronautical cluster founded in 1952 the Simulation Council where unclassified information were

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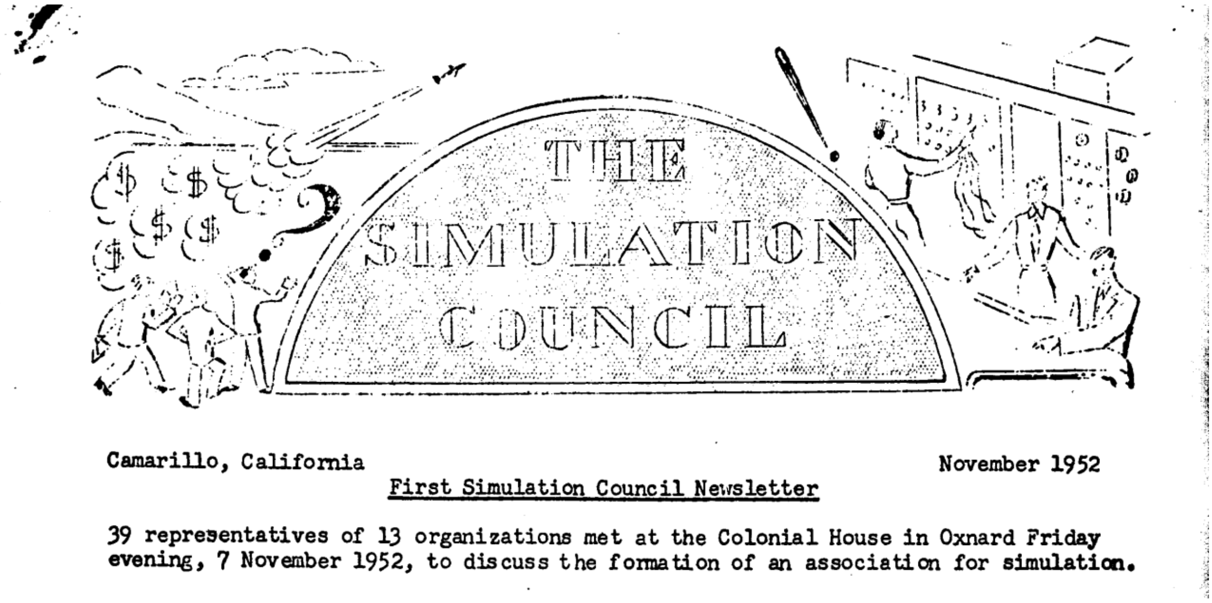
[77] For the use of analogue computing in the NASA project X15 see Gene Waltman, *Analog Flight Simulation at the NASA's Flight Research Center*, Washington, D.C., 2000. For the philosophical foundation of simulation studies see Gabriele Gramelsberger (ed.), *From Science to Computational Science,* Zurich 2011 and 2015.

[78] McLeod, Ten Years, (cf. note 61), 3.

79 Philbrick/Stark/Schaffer, Electronic Analog (cf. note 48).

80 Philbrick et al, Electronic Analog (cf. note 48), 67.

exchanged at meetings and published in a monthly newsletter that appeared since 1955 as supplement in the journal *Instruments and Automation*.[81] The following figure shows the title page of the Simulation Council News Letter.



THE SIMULATION COUNCIL

Camarillo, California **November 1952**

First Simulation Council Newsletter

39 representatives of 13 organizations met at the Colonial House in Oxnard Friday evening, 7 November 1952, to discuss the formation of an association for simulation.

Figure: Simulation Newsletter

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[81] For the newsletters 1952 to 1954 see http://www4.ncsu.edu/~cwm/sc-newsletters. For the August 1957 newsletter see *Instruments and Automation*, 1957, 1515–1520.

The Electronic Associates Incorporation (EAI) became a major producer of electronic analogue machines and offered for the aeronautical industry simulation services in its computer centres in Los Angeles, Princeton and Brussels (founded in 1957), see figure 14. These centres, supported by the EAI *User's Group Communication Newsletter* and EAI's *Analog Computer Application Bulletin*, also could be seen as an important institutionalization of analogue computing.[82]

Figure 14: EAI Computer Centres 1961[83]

Compared to analogue machines digital computers could compute with a higher degree of accuracy. This property was used in hybrid simulation settings to compute trajectories of rockets, where the correction of the rocket path due to RADAR signals was conducted in real time by digital machines, for example on Univac 1104.[84] The real time simulation on analogue machines was only possible for

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[82] EAI flyer on its computer 231R in 1961, source: Analog Computer Museum, Library, Bad Schwalbach, Germany, http://www.analogmuseum.org/english/library.html, http://www.analogmuseum.org/library/eai_usersgroup_newsl_small.pdf, http://www.analogmuseum.org/library/eai_appl_bull_no1.pdf.

[83] See note 79.

[84] Small, *Analogue Alternative* (cf. note 3), 147 – 152. For the hybrid installations see King/Gelman, *Experience with Hybrid Computation*, (cf. note 12). Ulmann, *Analog Computing* (cf. note 7), 151.

settings based on ordinary differential equations. If the models were based on partial differential equations, their solutions had to be attained by several steps that consumed time and where real time simulations were not possible anymore.[85] The high performance of electronic analogue computers for solving ordinary differential equations with one variable could be extended to the solution of partial differential equations of two variables x and y by coupling two analogue computers. With constant y the equation for x was solved on analogue computer one and the result was transmitted to analogue computer two, which solves the equation for y with constant $x+\Delta x$.

After the first boom in analogue computing 1945–1955 induced by guided missile projects, the rapid acceleration of the Atlas rocket program since 1954 induced the second boom in analogue computing. When Convair received the order to build the ICBM Atlas in the early 1950s, the warheads with thermonuclear weapons were still very heavy. Therefore, the Atlas rocket had to be equipped with powerful rocket motors and a high and stable rocket body. John von Neumann mediated between the R&D laboratories, which produced thermonuclear weapons, and aircraft manufacturers, which produced rockets as carriers. He was appointed in 1953 to the Teapot Committee of the DoD, which advised on the strategy of ICBM weapons.[86] In 1954 he became Chairman of the successor committee, the ICBM Advisory Board. There he took the view that the weight of a thermonuclear weapon could be reduced to 1500 pounds by the end of the 1950s. For the Atlas rocket development, this meant that a lighter, leaner rocket had to be designed. A conflict developed with Convair, which did not want to deviate from the original Atlas plans. In addition, the committee considered Convair's role as prime contractor obsolete. In this role, Convair was to outsource the main components of the missiles, such as motors, controls and electronics, to other contractors, build the missile body and carry out final assembly. The committee saw the new Atlas project as a gigantic project, comparable to the Manhattan project to build the atomic bomb. With its Fordist management structures derived from war production, rigid controls, and mere average pay for engineers, the Committee considered Convair inappropriate to manage the major Atlas project.[87] The accusation that Convair was too Fordist is remarkable and probably unique in the history of industrial rationalisation. This showed that Fordism had reached its limits in California's high-tech industry.

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[85] Electronic Associates Incorporation, EAI (ed.), *Handbook of analog computation*, Long Branch 1967, 279–287. Ulmann, *Analog Computing* (cf. note 7), 119.

[86] Hughes, Prometheus, (cf. note 2), 93. John von Neumann was also member of the committee that chose in April 1945 the targets of the first atomic bomb, amongst others Hiroshima, see Rhodes: Atomic bomb, (cf. note 73), 626.

[87] Hughes, Prometheus, (cf. note 2), 127.

The Committee was looking for a project management with flexible structures, a stimulating campus atmosphere and high salaries that would attract the country's best engineers. The arms boom swept the job market empty for engineers and scientists, and the research labs advertise that their buildings were designed like hotels in large parks.[88] The Bell Telephone Laboratory moved from the ugly industrial area of Manhattan to a nice campus in New Jersey. Simon Ramo and his collegue Dean Wooldridge had already set up the desired flexible structure in the company Hughes Aircraft as heads of the electronics department with 15,000 employees. The committee decided to terminate the contract with Convair and assigned the newly founded Ramo–Wooldridge Corporation with the design and the project management for the Atlas program and the set–up of a large R&D–lab (cf. figure 15).

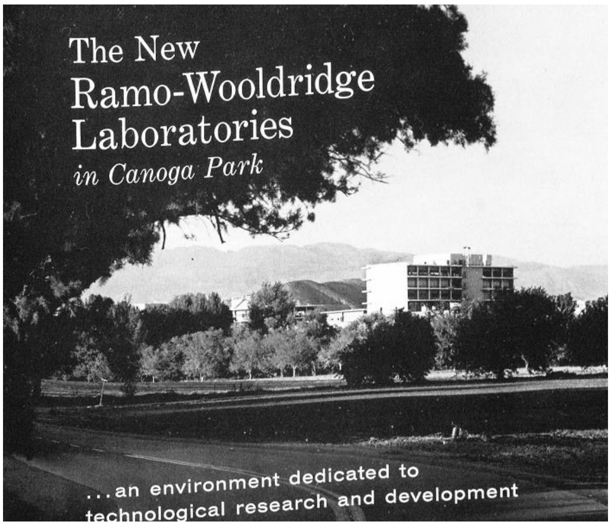

Figure 15: Ramo–Wooldridge's R&D Campus as recreation scenery
(Source: Datamation, 1960, no.1, p. 46)

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[88] For the shortage of engineers and scientists see John Krige: American Hegemony and the Postwar Reconstruction of Science in Europe, Cambridge (Mass) 2006, p. 195.

Convair retained the contract to build the missile body and carry out the final assembly. The Ramo–Woolridge Corporation in Los Angeles expanded with a staff of 5000 persons. Besides project management, this corporation maintained a large computing lab with hybrid computers for simulation studies of the rocket Atlas. Convair built a factory in the region of San Diego for the production the Atlas. This rocket consisted of 100,000 parts that were delivered to the factory by a supplier network consisting of 3,500 suppliers.[89] Simon Ramo and Dean Wooldridge rose to the top of the high tech scene in California and were honored 1957 with a cover story in Time magazine. In the standard accounts of the digital computer's history, these two leading persons are completely unknown.

Figure: Simon Ramo and Dean Wooldridge in Time Magazine 1957

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[89] Small, *Analogue Alternative* (cf. note 3), 147 – 152. For the project Atlas see Gainor, Atlas (cf. note 28). Gunston, *Illustrated Encyclopedia* (cf. note 22), 62. Hughes, *Prometheus* (cf. note 2), 69–140. For a photo of the research campus of Ramo–Wooldridge Corporation in Canoga Park, Cal., see figure 15.

When by 1957 the USSR launched the Sputnik satellite into the orbit the United States responded with a large space program that induced the third boom in analogue computing. In 1958 the US government transformed the National Advisory Committee for Aeronautics (NACA) to the strong unit National Aeronautics and Space Administration (NASA) that incorporated the Army's Jet Propulsion Laboratory in Pasadena, California, and Army's ABMA where von Braun's group conducted R&D with 4000 persons. Nasa's budget rose from 100 million Dollar to 1 billion.[90]

In June 1960 EAI won contract on 1.5 million Dollar to supply NASA's Langley Research Center with five fully expended electronic analogue computers PACE 231R systems. Those systems were used for various aspects of the Mercury project, including space station rendezvous. It was also used for the simulation of missile launches and satellites. EAI communicated this project as the "The World's largest analog Installation." The following figure shows these computers.[91] The great number of R&D–studies supported by analogue computers the NASA conducted can be seen at its web site https://ntrs.nasa.gov/search.jsp offering technical reports.[92]

Figure 15: Analogue Computer EAI 231R prepared for Langley's computing center in 1961[93]

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[90] Roger Bilstein, History of Naca and Nasa, 1915 – 1990, Washington, D.C., 1998, 48s.
[91] Datamation, May 1961, 8. For the 231R computer see Ulmann, Analog Computing (cf. note 7), 103.
[92] For example: Sidney A. Batterson, A study of the dynamics of airplane braking systems as affected by tire elasticity and brake response, Langley 1965, Technical Note D–3081. Analog simulation of a pilot-controlled rendezvous, by Roy F. Brissenden, Bert B. Burton, Edwin C. Foudriat and James B. Whitten, Technical Note D–747, Langley 1961.
[93] Datamation, 1961, May, 8.

3.7 Digital Computing with the IBM 604 calculator

Although there was a great wave in analogue computing after 1945, IBM had difficulties to identify the new market for scientific and engineering computing besides its traditional market of administrative computing as the study of Atsushi Akera pointed out.[94] So IBM could not participate on the flood of contracts the DoD issued for the defense industry. The new calculator IBM 603 based on electronic tubes IBM presented in the administrative context of the New York Business Show in September 1946. But it was only produced in a lot of 100 items.[95] Also followed IBM the marketing campaign for the digital computer – the only one that existed was the ENIAC – John von Neumann raised in the New York Times[96] and built in 1948 the SSEC as a showcase for its New York Headquarter in Manhattan. Neither the decision to build the SSEC was based on an urgent request of the western aeronautical cluster nor served the machine special needs of the defense industry but computed the position of the moon.[97]

As late as 1948, IBM responded to the needs of the aeronautical industry and offered the 604 digital electronic calculator, endowed with a rapid arithmetic unit that consisted of 1100 electronic tubes. It used punched cards for the input and output of data and could quickly carry out elementary arithmetic operations with its electronic unit and be programmed up to 60 steps, but without the ability to proceed loops and calls on subroutines. So, it was one of the first programmable digital computers with an electronic arithmetic unit in history. The IBM 604 computer was basically built like the Mark I computer from Harvard and the ENIAC. Numbers were held as digits on base 10 in accumulators and moved back and forth between them, but a main memory was absent. An addition was made by turning the single digit by an amount like a wheel. This machine operated with a binary representation of the decimal system.[98] The paradigm was the IBM punch card tabulating machine with counters in which each digit was represented by a wheel displaying the numbers 0 to 9. In a similar way, in the 604 machine the digits were represented by banks of tube flipflops. Three bits represented the numbers 0 to 4. A leading bit showed if this representation should mean the numbers 5 to 9.[99] So four flipflop tubes were sufficient for representing a digit or counter from 0 to 9,

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[94] Akera, *Calculating* (cf. note 1), 227.

[95] Phelbs, (cf. note 88), 258.

[96] New York Times, 15 Februar, 1946, New York Times, 14 December, 1947.

[97] Campbell–Kelly et al., *Computer* (cf. note 1), 115.

98 ERA (ed.), High Speed Computing Devices, McGraw-Hill, New York 1950. Akera, *Calculating*, (cf. note 1), 227. Michael Williams, *A History of Computing Technology*, Englewood Cliffs 1985, 256.

99 Byron Phelps, 'Early Electronic Computing Developments at IBM', *IEEE Annals of the History of Computing*, vol. 3, issue 7, 1980. For the binary coding of decimal numbers in the Bell Labs see also Paul Ceruzzi, *Reckoners: the prehistory of the digital computer. From relays to the stored program concept, 1935 – 1945*, Westport 1983,

within a number system on base 10. An additional flipflop was needed to hold the carry when the counter moved from 9 to 0. The flipflops were driven by 6J6 double triodes, which caused some reliability issues. The overall availability (including maintenance) attained 85 – 90 %. The 604 machine was widely accepted in the aeronautical industry and produced 2500 items up to 1955.[100] In 1949, the IBM 604 got a more advanced successor, the IBM Card Programmed Calculator (CPC), which was developed by IBM's lab in Poughkeepsie in collaboration with the Northrop Aircraft Corporation at the Los Angeles aeronautical cluster (see below).[101] So the incentive for this development came from the aeronautical industry. The main improvement in the CPC when compared to the 604 was the printing unit, and additional memory units had a greater capability for keeping temporary results. But only 200 CPC items were built. Many reports on the CPC have appeared, whereas the 604 – although representing one of the first programmable digital computers with an electronic arithmetic unit in history – was completely under-researched until 1997. The second edition of Michael William's book "History of Computing Technology" of 1997 filled this gap.

The digital computing capabilities of the IBM 604 and CPC were used by the aeronautical industry to solve the eigenvalue problems (roots) that arise in stability considerations of airframe vibrations and control systems. According to the control theory the real parts of the roots had to be negative in order to assure stability. W. Hunter and R. Johnson from Douglas Aircraft explored the roots of a polynom of degree 20 with the aid of the IBM 604 machine. Furthermore, they used the IBM 604 to calculate the transfer functions of the components in a guidance system for the frequency analysis.[102] The block diagram of the guidance system is shown as follows:

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65. For the tabulating machines see my working paper The First Informationexplosion. The Role of Punch Card Technology in the Office Rationalization in Germany, 1910-1939. Working Paper on the History of Computing No. 1/2017. www.vahrenkamp.org/files/Punch_Cards_Vahrenkamp_WP1_2017.pdf .

[100] Martin Weik, *A Survey of Domestic Electronic Computer Systems*, report no. 971, Aberdeen 1955, 58. John Sheldon and Liston Tatum, (cf. note 41), 36.

[101] Akera, *Calculating* (cf. note 1), Ceruzzi, *History* (cf. note 1).

[102] W. Hunter and R. Johnson, 'Analog–Digital Techniques in Autopilot Design', *Western Computer Conference*, Los Angeles, 1953, 119–127.

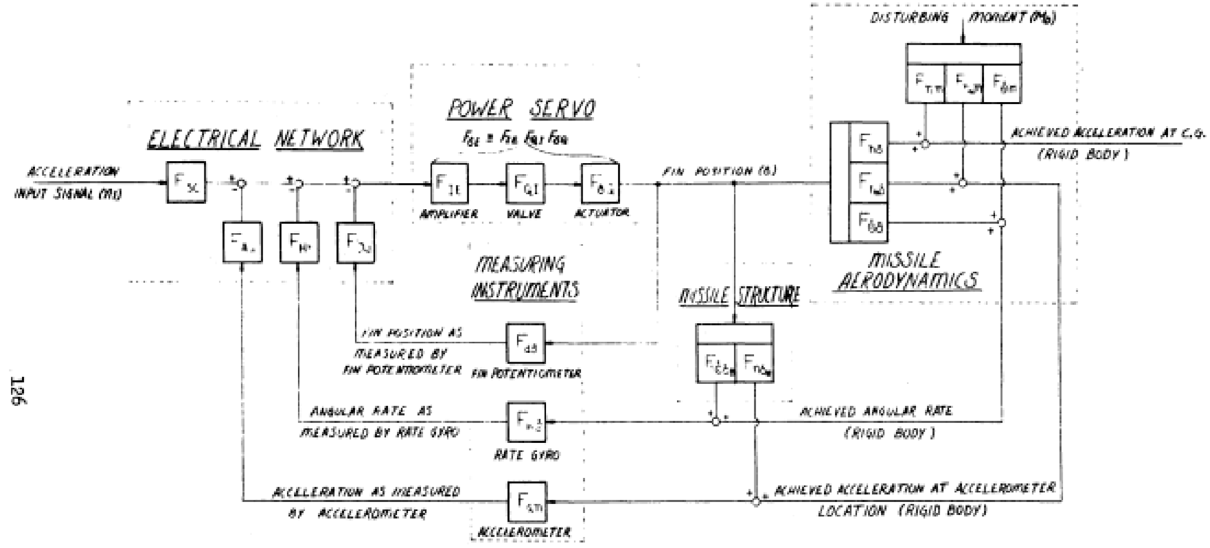

Figure 16: Block Diagram of a Guidance System

200 pieces of external data went into these solutions for the transfer functions, which were then repeated around 100 times until they reached a stable state. The engineers had to compute transfer functions of the form

$$F_{oi} = \frac{A_0 + A_1P + A_2P^2 + A_3P^3 + A_4P^4 \ldots}{B_0 + B_1P + B_2P^2 + B_3P^3 + B_4P^4 \ldots}$$

Only with the aid of a digital computer the engineers could perform each of these transfer function calculations in two hours. Without the computer, the frequency analysis would have lasted several weeks. The IBM engineers John Sheldon and Liston Tatum reported on further applications of the CPC machine in jet engine design and helicopter design.[103]

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[103] John Sheldon and Liston Tatum, (cf. note 41), 30.

4 Digital Computing at Northrop

In the case of Northrop, no one would have concerns made over Convair that rigid Fordist management structures hindered scientific and technical innovations. On the contrary, Northrop's innovative achievements were remarkable, and numerous spin-offs placed the new ideas on the market of defense products[104], as can also be seen from the CPC–project and the MADDIDA project. Many publications appeared on digital computing at the Northrop Aircraft Corporation in secondary sources, but no publications were made on analogue computing.

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[104] Sprague, *Western View* (cf. note 20), 687.

4.1 The BINAC at Northrop

The first experience with digital computing at the Northrop Aircraft Corporation was a failure. In 1947, a contract with John Mauchly‘s and John Eckert’s firm Electronic Control Company was made to deliver a high speed digital BINAC computer, to be used to guide the Snark missile. When the device was delivered in 1949, it did not operate successfully at the facility of Northrop in Hawthorn, California. Therefore, the project ended as failure.[105] The order to Electronic Control Company was accompanied with a wink, since nobody expected that the BINAC digital computer, with a weight of two tons, would be suitable for Snark. But the order was a way to support the young computer company, with a 100,000 dollar contract from the Pentagon.[106]

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105 Nancy Stern, ‘The BINAC: A Case Study in the History of Technology’, *IEEE Annals of the History of Computing*, vol. 1, no. 1, 9-20, July 1979.
106 Eckdahl et al. (cf. note 10).

4.2 The IBM CPC machine at Northrop

Northrop's second attempt was successful and shows a cautious approach to digital computing. Paul Ceruzzi sketched a lively image of the aeronautical industry on the West Coast, but completely omitted analogue computing. Instead, he underlined the need for digital computing at Northrop Aircraft.[107] One example is how much runway an airplane needs to take off. This length depends on several variables, such as the weight of the airplane, temperature, humidity and barometric pressure. For each small variation in the value of one variable, the formula must be computed to give a table for all the combinations. For this tedious task, the engineers at Northrop Aircraft Corporation coupled an IBM 604 multiplier with an IBM tabulating machine, for printing of the results on paper. The engineers dubbed this procedure the "poor man's ENIAC", indicating that the funding policy for the ENIAC did not meet the needs of aircraft industry.[108] Northrop Aircraft asked IBM to develop an extended version of this machine. Atsushi Akera described the cooperation between Northrop and IBM's lab in Poughkeepsie, New York.[109] Therefore, the demand came from West Coast aeronautical customers. The machine, called the Card Programmed Calculator (CPC), linked a multiplier IBM 604 with a memory unit (based on electrical–mechanical relays) and a tabulator for printing the computed results. In 1949, it successfully appeared on the market to cover engineering computations. IBM produced more than 200 units of this type against the background of Cold War R&D, but its predecessor, the electronic calculator IBM 604, was produced in a quantity of 2,500 units.[110] With the CPC machine, the table of values for the length of a runway could be easily computed. For every new value of one of the variables, only two cards had to be exchanged in the stack of cards and the "program" could run again to compute the new result.[111] Between 1949 and 1955 52 papers were published on applications of the CPC machine in science and 58 papers on the successor CPC II.[112]

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107 Paul Ceruzzi, *Beyond the Limits,* (cf. note 2). For the computing of a runway length with a high speed digital computer IBM 701 at Douglas Aircraft Corporation see C. Baker, 'The 701 at Douglas, Santa Monica', *IEEE Annals of the History of Computing*, vol. 5, 1983, no. 2, 187-193, here 193.

108 Bashe et al. (cf. note 7), 70.

109 Akera, (cf. note 1), 238.

110 Martin Weik, *A survey of domestic electronic digital computing systems*, Washington: OTS, 1955, 57.

111 Ceruzzi, (cf. note 2), 36s.

[112] Bibliography on ther Use of IBM Machines in Science, Statistics, and Education, IBM New York, January 1956.

4.3 The MADDIDA and John von Neumann

In 1949, in the context of the SNARK missile project, the Northrop Aircraft Corporation built a differential analyser called MADDIDA, based on electronic means of logical circuits with germanium diodes und used a magnetic drum as its main memory. MADDIDA was a digital computer that deviated from the von Neumann architecture. Different to electronic analogue computers that used the DC–amplifier, MADDIDA was purely digital and based on an invention by Northrop's engineer Floyd Steele of a binary incremental slope computer.[113] The following figure from Steele's patent shows how the slope computer converts the slope of a function to a sequence of pulses. The more the slope decreases the broader are the time distances between the pulses. This computers remindes of the digital differential analyser that Irvin Travis 1940 proposed.[114]

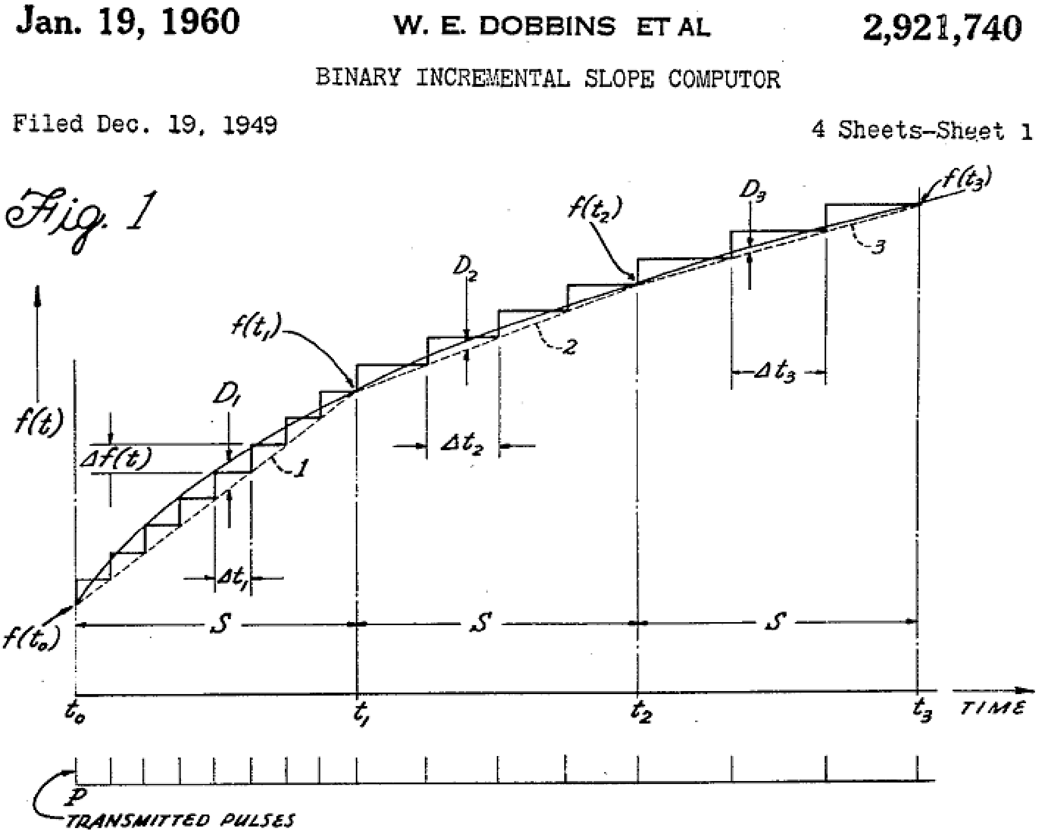

Figure 17: Steele's Patent of the slope computer (Source: Google Scholar).

Although not a general-purpose machine, the MADDIDA was ideally suited to a broad range of engineering work at Northrop, especially to solve differential equations. Its magnetic drum recorded

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[113] Sprague (cf. note 20). Eckdahl et al. (cf. note 10). Thomas Bartee, Irwin Lebow and Irving Reed, *Theory and Design of Digital Machines*, New York, 1962, 252. The patent for the binary incremental slope computer was filed on 19 December 1949, patent number 2,922,740 (accessible by Google Scholar).

[114] Haigh et al., ENIAC, (cf. note 8), 29.

the millions of data bits that were generated in aircraft development, for example in wind tunnel experiments, and reduced them to their main parameters. Because MADDIDA used a magnetic drum as memory, its performance was slow so that it could not be used for real time simulations studies, compared to the speedy electronic analogue computers that were based on the DC–Amplifier.[115]

In contrast to the large ENIAC and BINAC computers, MADDIDA's size was comparable to that of a refrigerator. In 1949, Northrop's press release stated : "The advances in MADDIDA in terms of simplicity and miniaturization are of great significance to the scientific and business world. A desk-side mechanical brain."[116] The following figure shows the development team of MADDIDA. Northrop sold some copies to the West Coast laboratories, but quit the commercial market after two years due to lack of capital.

Figure 18: Development team with three MADDIDA machines of Northrop Aircraft 1949. (Computer History Museum Mountain View, document no. 10885, 102710219).

Northrop published a booklet in December 1950 how to use MADDIDA and underlines its small deskside size, cf. the following figure. The booklet addressed to the aeronautical industry and described applications: "For the solution of complex aerodynamic problems such as flight trajectories; aerolastic problems of wing and body design; flutter and vibration problems; control problems; jet, rocket and other propulsive device type of design problems; stress and structure analysis."

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[115] Vance, The Role of Analog (cf. note 63), 26.

116 Computer History Museum Mountain View, document no. 10885, 102710219.

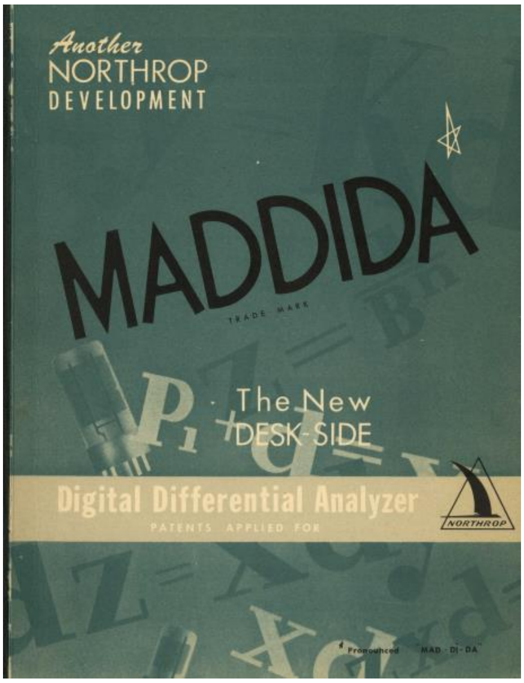

Figure 19: Northrop’s Booklet of MADDIDA 1950
(Source: www.bitsavers.org)

For a demonstration, Northrop sent the MADDIDA from Los Angeles to the Institute for Advanced Study (IAS) in Princeton, New Jersey, by air freight in 1950. John von Neumann – whose IAS computer was not in action before 1951 – was impressed by the plug and play ability of this computer. Under his supervision, MADDIDA computed some values of the Bessel function.[117] It is not quite clear why von Neumann saw – after this MADDIDA demonstration – his IAS machine as superior to the currently available electronic analogue computers for solving differential equations. In his letter to the Northrop Company on 14 March 1950, he expressed thanks for the MADDIDA demonstration, but omitted the issue of differential equations and did not acknowledge MADDIDA as a tool for solving these equations.[118] This is surprising insofar as for the broad field of differential equations – a field that was, according to the biography of William Aspray, most important for von Neumann’s work in meteorology and nuclear weapons[119] – analogue computers could deliver solutions very easily and quickly. But in his letter to Northrop, von Neumann expressed his wish that MADDIDA “is obsoleting the analogy type differential analyzer in its mechanical, as well as its electrical form.”

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[117] ‘Maddida’, IEEE Annals of the History of Computing, vol. 9, 1988, no. 3, 357 - 368. Ceruzzi (cf. note 2), 25-30. Dag Spicer, ‘Maddia – A bridge between worlds’, *Core*, September 2000, 6-9 (www.Computerhistory.org). The MADDIDA booklet of Northrop, Hawthorn 1950: *The new desk–side Differential Analyser* (http://www.bitsavers.org/pdf/northrop/maddida/MADDIDA_Brochure_Dec50.pdf). Eckdahl et al. (cf. note 10).

[118] The letter is published in Eckdahl et al. (cf. note 10).

[119] William Aspray, *John von Neumann and the Origins of Modern Computing*, Cambridge, Mass., 1990. Vladimir Zworykin made 1945 a proposal for an analogue computer for meteorological computations, as Aspray wrote, 130.

The ONR supported the „Numerical Meteorology Project“ with five researchers at the IAS since 1946. But only as recently as 1952 could the numerical results for weather forecasting be derived on the IAS computer.[120] Already on the ENIAC von Neumann integrated the Barotop Vorticity Differential Equation for weather forecasting,[121] although digital computers in the 1950s had such tiny memories that a solution of a system of differential equations could be difficult to obtain.

Whether there was a serious contest at the IAS between digital and analogue computers to solve differential equations is an unanswered question. Even in von Neumann's neighbourhood, electronic analogue machines were being built. On 21 November 1950, the RCA lab in Princeton demonstrated its Typhoon computer with a press release that von Neumann must have noticed.[122] The parallel funding of the RCA lab and the weather group at IAS sheds light on the completely uncoordinated funding policy of ONR. RCA developed an electronic analogue computer and the weather group used the digital IAS Computer. There was no request of ONR to use the RCA computer for the weather group's computations.

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[120] Thomas Haigh, Mark Priestley and Crispin Rope, *ENIAC in Action*, (Cambridge, Mass., 2016), 214-220. George Dyson, *Turing's Cathedral. The Origin of the Digital Computer*, (New York, 2012), chapter 9, Aspray, *Neumann*, (cf. note 106), 129-154.

[121] J. Charney, R. Fjörtoft and John von Neumann, 'Numerical Integration of the Barotop Vorticity Equation', *Tellus*, vol. 2, 1950, 237-254.

122 Small, General Purpose, (cf. note 3), 11.

5 Success Stories on Digital Computing

Since the 1960s, a special form of success story has developed that emphasized the digital computer but left the analogue computer unmentioned to push the latter into the background. Three texts are presented below.

5.1 Beyond the Limits without electronic analogue Computers

Paul Ceruzzi's book *Beyound the Limits* 1989 is a masterpiece of narrative technique.[123] He avoided any reference to the use of electronic analogue computers in the West Coast aircraft cluster. Instead, he talked about the use of Linear Programming at the RAND Corporation in Santa Monica in 1948 and about the further development of the IBM computer 604 to the CPC at Northrop Aircraft, i.e. about digital computing technology. Ceruzzi does not mention that the problem of aircraft fluttering can also be solved with analogue computers, as had be shown above with the example of Douglas Aircraft. Ceruzzi takes great care not to mention the electronic analogue computer. Instead, he emphasizes on page 57 that the mechanical analogue computer would have reached a high level in 1950, when Reeves Instruments had already installed 60 electronic analogue computers in the aircraft industry. To illustrate the mechanical analogue computer, he shows on page 56 a large figure of an automobile differential gear, but he does not show any figure of the Boeing or the Goodyear computer (cf. figure 1 and 9 in this text). On pages 52 and 62 he mentions the Typhoon and Cyclone projects, without mentioning the electronic analogue computer.

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[123] Cf. note 2.

5.2 Computer Power at Huntsville: An IBM Success Story

Unlike EAI, the supplier of analogue computers, IBM brought success stories about digital computing on rocket R&D into circulation. On the occasion of the delivery of its transistorized mainframe computer 7090 to Huntsville in 1960, IBM attempted to give the impression to the public with a launched article in the datamation magazine that computing on the rocket test site Huntsville consisted only of digital computing, and completely embezzled the role of analogue computing in the simulation of rocket flights.[124] In their 2021 book on the history of computing Thomas Haigh and Paul Ceruzzi uncritically repeat the IBM success story.[125]

The text in datamation is enhanced by interviews with Wernher von Braun, who has been the star of the Space Program since the successful launch of the first US satellite, and with Helmut Hoelzer, who was head of the Huntsville computer department until 1970. Hoelzer invented the electronic analogue computer in Germany 1943 and was the leading scientist in analogue computing in Huntsville.[126] The text pretends that there were no batteries of analogue computers to simulate rocket flights in Huntsville. According to the article in datamation, the Huntsville computation centre had extensive equipment of digital computers from various manufacturers, including four IBM mainframes 704 through 7090 purchased from 1956 to 1960. In addition, there were 7 Burroughs machines (205 and E-101), 10 Royal Mcbee LPC30s, and three IBM 605 card controlled calculators. The report says nothing about equipment on analog computers, although the head of the computation center, Helmut Hoelzer, is considered one of the inventors of the analog computer.[127] According to Tomayko's study of Nasa's computer use, numerous analog computers were operated in Huntsville.[128]

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[124] S. Lanzarotta, 'Computing Power at Huntsville', in *Datamation*, vol. 5, 1960, July, 18s.

[125] Thomas Haigh, Paul E. Ceruzzi: A New History of Modern Computing, MIT Press 2021.

[126] For Hoelzer's research on analogue computing in the V2 rocket project in Peenemünde see Thomas Lange: Computer Simulation in the V2 Rocket development, in: Gabriele Gramelsberger (ed.): *From Science to Computational Science*, Zürich 2011, pp. 85–96.

[127] Thomas Lange: Helmut Hoelzer — Inventor of the Electronic Analog Computer, in: Raúl Rojas and Ulf Hashagen (eds.): *The First Computers: History and Architectures*, MIT Press 2001, pp. 323–348.

[128] James Tomayko: Computers in Spaceflight. The NASA Experiment, NASA Contractor Report 182505, 1988, p. 283.

Helmut Hoelzer 1960. Source datamation, July 1960, p. 30.

On June 15, 1960, datamation magazine interviewed Helmut Hoelzer and asked him about his experiences at the Peenemünde rocket development station during the Nazi era. He spoke of a lack of simulation capabilities to simulate rocket tests on a computer. Instead, about 1000 experimental launches of the V2 rocket, officially designated Aggregat 4, were conducted. According to this interview, Hoelzer's computational department at Peenemünde for calculating the V2's trajectory consisted of 12 engineers and 40 female computers, known in German as Rechenmädchen, for computational tasks on desk calculators. According to Tomayko's study, Hoelzer developed three analog computers at Peenemünde at once, which worked on the basis of electron tubes and performed various tasks.[129] The first computer was installed in the V2 and controlled the angle inclination of the rocket. The second analog computer was also built into the V2 and controlled

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[129] James Tomayko: Helmut Hoelzer’s Fully Electronic Analog Computer, in: *Annales History of Computing*, vol. 7, July, 1985, pp. 227– 240.

deviations from the specified trajectory. The third computer was used on the ground to simulate the flights of the V2.

5.3 The IBM 701 at Douglas Aircraft

In May 1953, an IBM 701 high speed digital computer was delivered to Douglas Aircraft, and C. Baker reported on the application of this computer as classic success story in the Annales for the History of Computing in 1983. This story can serve as an example how the promotors of digital computing exaggerate and suppress the story of the analogue computer. Although the analysis of wing flutter was conducted by analogue computers before at Douglas, as shown above, with the design of the new model DC–7, Baker gave the impression of having solved this problem with a high speed digital computer. With this instrument one could perform simulations for the first time: "For the first time it was possible to model and simulate in detail the essential characteristics of a contemplated design before the aircraft was built and flown."[130] As Baker reported, the first models of the DC–7 were delivered before April 1954. It is not very convincing to think that, between May 1953 and April 1954, all the setting up and programming of the 701, and the simulation and building of the airplane could have been performed. If one takes the production process of the examples of the B–17 or B–29 bombers,[131] the procurement of parts at subcontractors alone required a lead time of two years, in which machines had to be tooled, parts to be produced and shipped. If one assumes one year for design and one year for final assembly and testing, all these tasks would have had to have been started by April 1950. Therefore, the DC–7 was designed without the aid of the 701.

From Baker's success story, it is not quite clear why Douglas Aircraft installed the IBM 701. With a marketing measure before delivery of the 701, IBM acquainted Douglas' engineers with the 701 by a series of seminars. As a reason to procure the 701, Baker refers to the speed of the machine: A matrix multiplication was carried out in 2 seconds, compared to 2 or 4 minutes by an IBM CPC machine. The 701 was seen as a hundred times quicker than the CPC. On the other hand, the 701 machine had a rental cost of $15.000 a month, 40 times the monthly salary of an engineer, as Baker pointed out. Eventually, Douglas Aircraft installed five 701 machines at their different production facilities. In 1953, Douglas had already to proceed a volume of 5 million punch cards per month through the CPC machines. As McClelland and D. Pendery put it, it was "the CPC that developed the market for long sequential calculations in the West. Thus when the 701 was marketed, many potential customers were already solving big problems and therefore understood the economic value of the machine."[132]

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130 C. Baker, 'The 701 at Douglas, Santa Monica', *IEEE Annals of the History of Computing*, vol. 5, 1983, no. 2, 187-193, here 192. See also W. McClelland and D. Pendery, '701 Installation in the West', *IEEE Annals of the History of Computing*, vol. 5, 1983, no. 2, 167–170.

[131] Michael O'Leary, *Boeing B–17 Flying Fortress*, Oxford 1998. David Willis, 'Boeing B-29 and B-50 Superfortress', *International Air Power Review*, Volume 22, 2007, 138.

132 W. McClelland and D. Pendery, (cf. note 109), 167s.

In aeronautical firms, a need for digital computing arose that the IBM 701 could satisfy, because the digital equipment in the IBM 604 had a lack of flexibility. Only “linear” programs could be computed, but no calls of subroutines (as square root, sorting or sinus) and no loops could be performed.[133]

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[133] H. Wolanski, ‘Application of Computing in the Aircraft Industry’, in: Preston Hammer (ed.), *The Computing Laboratory in University*, Madison 1957, 94. Wolanski reports on structural design analysis with the aid of IBM 701 at Convair Aircraft, Fort Worth, Texas, 100.

6 Conclusion

This paper shows the important role of computing machines in supporting the development of new aeronautical weapons. Other than the success stories of digital computing suggest, analogue computing played an important role in the aeronautical industry. Digital and analogue computing coexisted for different tasks. Analogue machines could solve differential equations and served as tools for simulation at the different stages of the airplane and missile design processes. The paper identifies three booms in simulation and shows steps towards the institutionalization of simulation. In the domain of dynamical system's simulation, the analogue computer prevailed until the 1970s. The leading role of analogue computing in the aeronautical industry one finds also in Great Britain during 1945 to 1965, as described by James Small. The same constellation one could expect in other countries with a strong aircraft industry in 1945, for example in the Soviet–Union. But this is open for further research. Also, for further research, the question remains open as to why the digital computer eventually covered the whole field of computing and appears now to be a natural trajectory towards modern computing.

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