AUG 14 1999
By RJL

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8 August 1999

Robert J. Lauson, Esq.
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233 Wilshire Boulevard, Suite 900
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Dear Mr. Lauson:

In response to your letter of July 20, 1999 I make the following two points:

1. My paper titled "On Algebraic Compilers and Planetary Fly-By Orbits" is published in *Acta Astronautica* Vol. 38, No. 12, pp. 895–902, June 1996 by Elsevier Science Ltd. (A copy is enclosed.) The addendum provides evidence, not subject to interpretation, which removes all question concerning the authenticity of my claim that the work described took place early in 1961. The two figures, which depict the Earth-Venus-Mars-Earth trajectories, labeled Fig. 26 and Fig. 27 on pages 118 and 119 of the Draper Anniversary Volume **Air, Space, and Instruments**, edited by Sidney Lees and published by McGraw-Hill Book Company in 1963, were made from negatives, numbered and recorded in the librarian's log at the MIT Instrumentation Laboratory (now called the Charles Stark Draper Laboratory) for the date 7 February 1961. A photo-copy of the appropriate page from that log is enclosed. This is conclusive proof that I successfully calculated the Earth-Venus-Mars-Earth trajectories no later than January 1961.
2. The enclosed letter from Arthur C. Clarke dated 12 February 1997 shows that Michael Minovitch is not the originator of the concept of gravity-assist propulsion. According to Clarke, this idea was known to those in the field of celestial mechanics since at least 1954 if not much earlier.

I trust these facts will put an end to this matter.

Very truly yours,

Richard H Battin

Richard H. Battin

cc: Edward F. Crawley, Head, MIT Department of Aeronautics & Astronautics
Charles M. Vest, MIT President
Thomas Henneberry, MIT Director of Insurance and Legal Affairs
Frederick I. Ordway III, IAA Committee Chairman on the History of Astronautics

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# ON ALGEBRAIC COMPILERS AND PLANETARY FLY-BY ORBITS†

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*(Received 7 June 1995)*

**Abstract**—This paper reports on two major technology events of great significance in the field of Astronautics which were conceived and developed at the MIT Instrumentation Laboratory during the decade of the fifties. It is a personal memoir by the author on two important topics which should be a part of the written history of our field.

Part one details the conception and development by Dr J. Halcombe Laning, Jr of "George", the world's first algebraic compiler for use on Project Whirlwind—MIT's first experimental all-digital computer. This was indeed challenging since Whirlwind at that time had but 1024 sixteen-bit words. Dr Laning began work in the summer of 1952 and the first version of the George compiler was finished in March of 1953.

In the early fifties many people were debating the feasibility of a system for translating algebraic formulae into computer programs which would allow the engineer to avoid the all too painstaking and error-prone task of writing programs using basic computer code. But Hal Laning was the first to do it.

In part two of this paper, the author explores the early concepts of energy exchange between a spacecraft and a planet during a close encounter of these two celestial objects. The fact that this energy transfer could be exploited for useful purposes in the development of interplanetary orbits was first documented in an MIT Instrumentation Laboratory report published in April of 1958. The topic has been the subject of recent papers at several IAF congresses, but they failed to recognize the early work at MIT. As a part of this important history, the author describes his own work to develop a round-trip orbit to Mars using the planet Venus for a gravity assist to shorten the flight time from three years to one and a quarter years. The first orbit of this type was obtained by the author on 26 January 1961. To the author's knowledge, no one has even suggested that practical three-dimensional multiple fly-by orbits had been constructed at an earlier date. Copyright © 1997 Elsevier Science Ltd

## 1. THE FIRST ALGEBRAIC COMPILER

In the early 1950s[1,2] the development at MIT of an all-electronic digital computer was well underway. Project Whirlwind, as it was called, was an enormous machine, completely filling a large building off-campus. Its memory, at that time, consisted of 1024 sixteen-bit words electrostatically stored on cathode-ray tubes. However, at the MIT Instrumentation Lab,§ where Hal Laning and I were employed, we had to make do with mechanical desk calculators. In 1952, the Lab acquired an IBM Card Programmed Calculator (CPC) which could perform 100 floating point calculations per minute and had for a memory 27 mechanical counters each holding a ten decimal digit number.

In the summer of 1952, following about six months experience as a user of the Whirlwind, Hal felt that computers should be capable of accepting conventional mathematical language directly, without having to recast engineering problems in an awkward manner using logic that was too far removed from the engineer's daily experience. Over the next few months he personally brought this idea to fruition with the development of the first algebraic compiler called "George" —from the old saw

*"Let George do it"*.

### *1.1 The development of "George"*

The first version of the George compiler was finished in March of 1953. The first non-trivial program executed by George was a set of six non-linear differential equations describing the lead-pursuit dynamics of an air-to-air fire-control problem. The power of this grandfather of all compilers was aptly demonstrated—the equations

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† Paper IAA-94-IAA.2.1.618 presented at the *45th International Astronautical Congress*, Jerusalem, Israel, 9–14 October 1994

‡ Senior Lecturer, Department of Aeronautics and Astronautics.

§ Now called the Charles Stark Draper Laboratory, Inc

In the lobby of the Draper Laboratory there is an exhibit in tribute to the pioneering achievement of Hal Laning for the development of "George" Indeed, Hal was elected to the National Academy of Engineering for "Unique pioneering achievements in missile guidance and computer science—the 'Q-guidance system' for Thor and Polaris and 'George' the world's first algebraic compiler."

were programmed in less than one hour, and successfully executed on the very first trial.

When a magnetic drum memory was added to the Whirlwind computer, Hal Laning encouraged Neal Zierler to collaborate in extending, perfecting, and documenting[3] the George compiler.

For historical interest I have included several examples of the George language from the user's manual[3]. The notation was constrained by the symbol availability on a Flexowriter, a specially designed typewriter that produced a coded pattern of holes in a paper tape. Since only superscripts were available, subscripts were indicated with a vertical slash prefix. There were available 23 functional subroutines designated $F^1$ through $F^{23}$ for square root, sine, cosine, etc. Below are several equations translated into the George notation:

$$
\begin{aligned}
a = 5^2 &\implies \texttt{a=5}^{\texttt{2}}, \\
b = (a-2)^{-2} &\implies \texttt{b=(a-2)}^{\texttt{-2}}, \\
c = (ab^3)^{-5} &\implies \texttt{c=(ab}^{\texttt{3}}\texttt{)}^{\texttt{-5}}, \\
x = 2(\sqrt{y}\sin z) &\implies \texttt{x=2(F}^{\texttt{1}}\texttt{(y)F}^{\texttt{2}}\texttt{(z))}, \\
x = \tan(y + \cos^{-1} z) &\implies \texttt{x=F}^{\texttt{4}}\texttt{(y+F}^{\texttt{6}}\texttt{(z))},
\end{aligned}
$$

The George system has provision for conditional and unconditional transfer of control denoted by CP and SP as well as the solution of ordinary differential equations using a fourth-order Runge-Kutta algorithm. The upper case letter D in the program denotes d d$t$. For example, to generate the solution of the differential equations

$$\frac{dy_1}{dt} = y_2 + 1 \quad \frac{dy_2}{dt} = -y_1 \quad y_1(0) = y_2(0) = 0$$

from $t = 2$ to $t = 10$ in unit steps using an integration time interval of $h = 0.5$, the appropriate George program would be

```
    t=2,
    h=0.5,
    y|^1=0,
    y|^2=0,
1   PRINT t, y|^1, y|^2.
    e=9.7-t,
    CP 3,
2   Dy|^1=y|^2+1,
    Dy|^2=-y|^1,
    e=-e,
    CP 2,
    SP 1,
3   STOP
```

The variable $t$ is automatically increased by the value of $h$ after the last equation that starts with a D is completed. The four substeps required by the Runge-Kutta algorithm take place automatically.

George was a usable system by May of 1953 and was introduced to the world in 1954 at a symposium in automatic programming sponsored by the Office of Naval Research. On 21 May 1954 John Backus of IBM wrote[4] to Hal Laning saying:

> "Last week I attended a session in Washington at which Professor Charles Adams [of MIT] described the system for translating algebraic formulae into computer programs which you and your associates have developed. After the meeting he gave us a copy[3] of the description by you and Mr Zierler.
>
> "My programming research group here is beginning work on such a system for IBM's newly announced 704 calculator. We would very much appreciate the opportunity to benefit from your work in this area. Our formulation of the problem is very similar to yours; however, we have done no programming or even detailed planning. Therefore, detailed discussions with you and some of your associates in this work would perhaps save us much time and duplicated effort."

Two weeks later in June of 1954 John Backus, together with the nucleus of his IBM FORTRAN team, visited MIT for a demonstration of George.

Two years later at the 1956 *ONR Symposium* Grace Hopper (one of the early spokesmen for automatic programming during the 1950s) addressed the meeting to discuss the previous two years of progress. In her introductory remarks[5] she said:

> "... Laning and Zierler's system of algebraic pseudocoding for the Whirlwind computer led to the development of Boeing's BACAIC for the 701, FORTRAN for the 704, AT-3 for the Univac, and the Purdue System for the Datatron ..."

Professor Donald E. Knuth (now Chairman of the Computer Science Department of Stanford and a member of the NAE and the NAS) was certainly impressed by George. In a letter[6] to Hal Laning dated 5 June, 1965 he wrote:

> "Thanks for sending me the copy of your work on the Whirlwind I interpretive compiler—which just astounded me! I certainly didn't expect to see such a sophisticated input language, especially since this is no doubt the first instance of algebraic translation ever implemented.
>
> "... I am writing a book on non-numerical computer techniques, and I am trying to get accurate historical information. I have included several paragraphs about your remarkable language.
>
> "... Also, can you tell me what influenced you to invent this epoch-making idea in the first place?"

In his history of "The Early Development of Programming Languages" written[5] with Luis Pardo and published in August 1976, Donald Knuth wrote:

> "In retrospect, the biggest event of the 1954 symposium on automatic programming was the announcement of [George] . . .
>
> ". . . the full user's manual[3] ought to be reprinted some day because their language went so far beyond what had been implemented before. The programmer no longer needed to know much about the computer at all, and the user's manual was (for the first time) addressed to a complete novice."

and in a personal letter[7] to Hal on 16 August 1976, Professor Knuth said:

> "Last weekend I amused myself by studying the vintage 1953 compiler listing you sent . . . It was remarkable how much logic you squeezed into 430 instructions . . .
>
> "The form of the object code was filled with surprises for me; thank you again for letting me have a look at this most innovative approach to formula translation."

### *1.2 "MAC" evolves from "George"*

The plans for a much expanded Whirlwind compiler were dropped when the MIT Instrumentation Lab acquired its own stored program digital computer—an IBM type 650 Magnetic Drum Data Processing Machine. In 1957, when tapes were available, Hal, with the help of Phil Hankins and Charlie Werner, began work on MAC—an algebraic programming language for the IBM 650, which was completed by early spring of 1958.

Over the years MAC became the work-house of the laboratory, and many versions were written to be hosted on the IBM 650, 704, 7090, and 360, as well as the Honeywell H800, H1800, and the CDC 3600. MAC was used for all of the MIT Apollo Project analyses and simulations in the design and development of the Guidance, Navigation and Control System for the Command and Lunar Modules. It was also installed at the NASA Manned Spacecraft Center in Houston and at other NASA prime contractor facilities. From the abstract of the report[8] "The MAC Algebraic Language System:"

> "the characteristics which most strongly distinguish MAC from more commonly used languages, such as Fortran, are a three-line source-statement format, which includes exponent, main, and subscript lines, and its vector matrix and derivative notation . . . a language which inherently possesses extraordinary visual clarity and is quite easy to learn."

and from the conclusions of the MAC report:

> ". . . for the category of the algebraic numerical problems for which it has been designed, MAC has been found to greatly simplify the creation and testing of programs. Although the language does not include many features found in Fortran, these shortages have rarely been felt at the Laboratory; however, there is no reason whatever why such features could not be added to MAC if desired."

The evolution from George to MAC involved a change in input device from Flexowriter (with upper and lower case letters and superscripts) to IBM punched cards. The output device was a tabulator which printed the contents of each card on a separate line. The goal was to make MAC as indistinguishable from standard mathematical notation as possible. My solution was to use three cards for each equation so that exponents and subscripts would assume their proper position in an equation. (The idea was offered to IBM to use in Fortran but was dismissed as being "too hard to keypunch.")

Below we illustrate the MAC language with some source statement examples taken from the report:[8]

```
E
M A = B + 2(C - D)
S
```

```
E      2        6
M P = Q  + R/D
S             J+1
```

```
E         N-1   2
M SIGMA = SUM (A  +3 B      )
S         I=1   I     AV,I+1
```

Next is a vector–matrix example where the overbar denotes a vector and the superposed asterisk signifies a matrix. The asterix is also used to denote the vector cross-product operation.

```
E -   * -    -
M L = M(V  * V ),  K = K + 1
S        3    6
```

This last example also demonstrates how more then one equation can be included on a single line.

The high-order language called HAL, used to program the NASA Space Shuttle avionics computers, is a direct offshoot of MAC. The principal architect of HAL was Jim Miller who was responsible for both the MAC system and all of the Apollo Mission digital simulations for the MIT Apollo Project.

John Backus[†] expressed great admiration for the work of Hal Laning. In 1991 he had occasion to write:[9]

> "... Dr Laning was the first person to conceive of and implement what we would now call a true compiler—a program that converts a *description of a computer program* into a real machine-language program that a computer can then execute whenever desired. It was this idea that has made the computer a really useful tool. Without programming languages and the compiler programs that translate these languages into running programs, the computer industry and all the benefits it has brought to society would have been greatly reduced–the programs that run computers would have been so costly and time-consuming to produce that the development of the industry would have been slowed by a large factor.
>
> "Before Laning, no one had conceived of and implemented an elegant and powerful language for expressing a computation (although there were examples of *very* much less sophisticated schemes to aid the programmer). His concepts of a programming language and of a compiler were completely original at the time. They were the beginning of the entire programming language and compiler business, which in turn made computers accessible to large numbers of users. I agree with the nominators that this development of Laning's was comparable in impact to the development of the first solid state devices. He certainly richly deserves the National Medal of Science for this work."[‡]

## 2. PLANETARY FLY-BY ORBITS

The launch of the Russian Sputnik on 4 October 1957 inspired Hal Laning, Elmer Frey, and Milt Trageser of the MIT Instrumentation Lab to undertake a small project to study the feasibility of an unmanned photographic reconnaissance flight to the planet Mars. After a six month effort, they published a report[11] outlining the design of a suitable vehicle for this purpose, a description of various trajectories, and possible methods for navigation and guidance. They also predicted:

> "It is the considered opinion of the authors that a research and development program to this end, initiated today, could reasonably be expected to lead to the launching of such a vehicle within the next five to seven years".

Unfortunately, I had been away from MIT for about one year when the Sputnik was launched. When I learned about the Mars reconnaissance mission, I hurriedly rejoined my friends at the MIT Instrumentation Lab. This project was too exciting to miss.[§]

### 2.1 *Orbit selection for the Mars mission*

The section on trajectories in the Mars report[11] was the work of Hal Laning. He concluded that

> "Other things being equal, the idea of entering orbit about Mars for an extended period is an appealing one, since it permits the acquisition of more complete scientific data than would otherwise be possible. On the other hand, a considerable amount of useful data could be acquired by a vehicle which simply passed by the planet without stopping."

—i.e., a Martian fly-by orbit. The latter was chosen because

> "It would appear that the nonstop orbit might be feasible at an earlier date than the other ..."

Hal explained

> "The main idea in the nonstop trajectory is that of a vehicle which makes two circuits about the Sun while the Earth makes three, passing near to Mars in the process."

Using numerical integration on an IBM 650, he calculated a sample orbit using trial and error to obtain appropriate initial conditions. Again from the report

> "The plot ... shows two coordinates of a three-dimensional trajectory calculated to leave Earth about 0700 GMT on 25 August 1958, arriving at Mars about 2300 GMT on 25 January 1959, and returning to Earth on about 6 October 1961. This trajectory, for which a characteristic velocity of 26,787 mph is quoted above, represents a first attempt by the authors at generating a suitable flight path and has in no way been optimized."

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[†] On 22 February 1994 the National Academy of Engineering issued a press release[10] "John Backus, the engineer who led the way for modern computer programming, today received the National Academy of Engineering's (NAE) prestigious 1993 Charles Stark Draper Prize—the world's largest award for engineering achievement. Backus received $375,000 and a gold medallion for his development of FORTRAN—FORmula TRANslation—the world's first practical general-purpose, high-level computer language."

[‡] Hal did not receive the National Medal of Science.

[§] A full size wooden model of the Mars probe spacecraft is displayed in the lobby of the Draper Laboratory. The Mars mission was never flown, but it did attract the attention of NASA[1] resulting in some small study contracts. Later came the prime contract for the Apollo guidance, navigation, and control system.

Hal provided a careful analysis of the effect on the solar orbit of a close pass of Mars. He pointed out that

> "In the vicinity of Mars the missile is travelling with a velocity slightly less than that of the planet in the tangential direction and with a positive radial velocity component . . . If the missile passes ahead of the planet . . . it will experience a vector change in velocity whose magnitude $\Delta v$ . . . for the trajectory considered . . . has a value of about 3600 mph. This change is more or less in the same direction as the missile velocity itself, and in such a direction as to reduce the speed. It would therefore appear that Mars is removing energy from the missile by its gravitational effect and that this extra energy must be supplied by a higher velocity in leaving Earth than might otherwise be required. The possibility at once suggests itself that by guiding the vehicle to the rear of Mars instead of in front of it, a gain in energy will occur and that a reduction in the required velocity in leaving Earth might be achieved."

In his trajectory analysis, Hal emphasizes the importance of the three-dimensional aspects of the mission—putting thereby the traditional Hohmann transfer in its proper perspective:

> "Another trajectory complication arises from the fact that the orbits of Mars and Earth are not coplanar. At first glance this complication would seem quite minor since the angle between the two planes is only 1.85 degrees. However, a trajectory followed by a vehicle moving solely under the influence of the Sun's gravitation must lie in a plane which contains the Sun. If this plane is also to include the position of Earth at the time of departure and the position of Mars at the time of arrival, and if these two positions are nearly 180 degrees apart as seen from the Sun, the resulting plane will possess a large angle of inclination to that of the motion of the Earth. As a result, either the 180-degree minimum velocity trajectory must be modified so as to intersect Mars' orbit at another position, or else the missile must undergo a further velocity change, at some point in midcourse."

### 2.2 *Martian fly-by orbits*

When I joined the small MIT team to prepare a system proposal for the Mars reconnaissance project, I soon realized that we did not know how to compute trajectories for the simple two-body, two-point boundary-value problem. The tools we needed for this work were not easily obtained. No one studied Celestial Mechanics unless he planned to be an astronomer and astronomers were not interested in designing orbits for missions to Mars.

I was successful in developing an orbit determination technique using pieced-conics for which the mission was divided into three parts—an elliptic solar orbit from Earth to Mars, a hyperbolic fly-by of Mars, and an elliptic solar orbit from Mars back to Earth. Although the outbound and return orbits were nearly in the plane of the ecliptic, the orientation of the fly-by plane was significantly inclined (by almost 90 degrees) to the Martian orbit. It was now apparent that any model which assumed coplanar orbits would be unacceptable.

Our orbit determination method was not only useful for the Mars probe, but became the basis of the major orbit-determination programs of JPL, the Navy and the Air Force. It was presented at the annual meeting[12] of the Institute of the Aeronautical Sciences in New York on 28 January 1959. One of these Martian orbits was illustrated on the cover of the March 1959 issue of the MIT Technology Review[13].

We used this method to support the Mars study project for NASA and confined our attention to trajectories whose flight times were of the order of three years and which had launch dates in the years 1962–1963. These missions, for which the space vehicle makes two circuits about the Sun while the Earth makes three, seemed to provide the greatest flexibility in launch window and passing distance at Mars without placing unreasonable requirements on launch system capabilities.

Our extensive effort on space trajectories was reported in a July 1959 MIT study[14]. The problem of optimum injection from an Earth parking orbit and other associated details were published the following year in yet another MIT study[15].

A volume of original contributions titled *Air, Space, and Instruments* was planned to honor Charles Stark Draper on his sixtieth birthday which would occur on 2 October 1961. Hal Laning and I contributed a chapter[16] on our trajectory work for interplanetary missions. Unfortunately, the actual publication of the Draper Anniversary Book was delayed by the publisher and it did not appear until early in 1963.

In our chapter for the Draper volume we summarized the study of the feasible range of interplanetary orbits with a systematic search using as independent variables the date of launch and the time-of-flight. The results were displayed by a series of contour maps in which launch date and time-of-flight are the axis coordinates. Contours were constructed, representing constant values of such quantities as injection velocity, location of the injection positions, and the relative velocity at the destination planet. For the Mars mission we plotted contours for injection velocities from an Earth parking orbit ranging from 38,000 to 42,000 feet per second.

This mode of presentation of possible orbital missions became quite popular when others began similar studies. Since some of the contour maps resembled pork chops, they later became known as "pork chop curves."

### 2.3 *Exploiting gravity assists during fly-bys*

During our rather exhaustive study of round-trip trajectories to Mars, we decided to include missions to Venus. Although the idea of sending our spacecraft to photograph Venus was not seriously contemplated (because of the Venusian cloud-cover), we were impressed by the reduction in mission time. Instead of three years, our Venus orbits had a round trip time of about 1.2 years with a return-trip time approximately twice that for the outbound leg. These Venus trajectories were first presented in August of 1959 during a symposium held at UCLA and published later in their proceedings[17].

The Venusian reconnaissance trajectories impressed me because of the proximity of the spacecraft orbit and the Martian orbit. Later I found the time to explore the consequences of this observation. The story is told in the Draper Anniversary volume[16]:

> ". . . it is of interest to note that the increased velocity introduced at Venus is sufficient to carry the spaceship on the return trip to a distance of about 1.35 astronomical units from the Sun. Since Mars at perihelion is only at a distance of 1.38 astronomical units, the interesting possibility arises of a dual contact with both planets with a total time-of-flight for the round trip just in excess of 1 year . . . The synodic periods of Venus and Mars are 584 and 780 days, respectively. Therefore, one can expect favorable conditions for round-trip missions to each planet individually to recur with the corresponding synodical frequency. On the other hand, roughly 2,340 days are required before any particular configuration of the three planets Earth, Venus, and Mars will be approximately repeated. Even then the likelihood of a configuration existing at all in the near future, which would admit of the dual mission, seems remote.
>
> "Nevertheless, on 9 June 1972, the ideal circumstances prevail. On that date a vehicle in a parking orbit from Cape Canaveral on the 100 degrees launch azimuth course may be injected into just such a trajectory at the geographical location of 5 degrees west and 18 degrees south and with an injection velocity of 39,122 ft per s. After escape, the vehicle will have velocity relative to the Earth of 15,000 ft per s. The first planet encountered will be Venus after a trip lasting 0.4308 year. The vehicle will pass 4426 miles from the surface of the planet and will thereby receive from the Venusian gravity field alone a velocity impulse sending it in the direction of Mars. The second portion of the trip consumes 0.3949 year and the spacecraft contacts Mars, passing at a minimum distance of 1538 miles from the surface. The trip from Mars to Earth takes an additional 0.4348 year, and the vehicle returns on 13 September 1973. This truly remarkable trajectory† is illustrated in Fig. 26.
>
> "It might be expected from previous remarks that similar conditions would exist approximately 6.5 years earlier. Indeed, the trajectory shown in Fig. 27 is possible on 6 February 1966, and is similar in all respects but one. With a departure velocity of 16,500 ft per s the vehicle contacts Venus after 0.4196 year and Mars 0.5454 year later with respective passing distances of 1616 miles and 7515 miles. Now, however, the encounter with Mars occurs quite far from the Martian perihelion. Thus, in order to catch up with the Earth, the vehicle must once again pass inside the Earth's orbit with the result that the return trip from Mars requires 0.8950 year."

It was very exciting indeed when the double fly-by finally worked. A large number of iterations on the IBM 650 had been required. The initial conditions for each iteration had to be key-punched and inserted in the card-reader. The output was produced on punched cards which then had to be listed on an IBM tabulator. The trial failed if the spacecraft were required to fly beneath the surface of either planet to obtain the necessary energy exchange to carry it to the next planet.

I sensed the importance of this result and saved the tabulator listing which included the date of the printout—26 January 1961. Today it is among my most treasured mementos.

Needless to say, I was most anxious to publish the result. Our chapter for the Draper Anniversary Book was already underway and the multiple fly-by orbit would provide a really dramatic climax for our contribution. I would have published it in a separate paper had I known that McGraw-Hill would slip their publication schedule for the Draper volume by more than a year.

My book[18] *Astronautical Guidance* was also underway at that time and, naturally, it would include the multiple fly-by story (see Chap. 5).

Although this was the first realistic multiple fly-by mission ever designed, it was not the first ever conceived. That distinction goes to General Gaetano Arturo Crocco who was Director of Research of the

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†Since I had discovered this trajectory on 26 January 1961, the launch date of 9 June 1972 seemed incredibly far off—over 11 years!

Air Ministry and a Professor of Aeronautics at the University of Rome, Italy. His paper[19] described an Earth to Mars to Venus to Earth mission of one year duration. The orbits were all coplanar; the velocity requirements were enormous; and the reversed itinerary prevented the best utilization of the gravity assist maneuvers. But it was published in 1956–one year before Sputnik.

The Crocco mission requires an excess hyperbolic velocity exceeding 38,000 ft per s owing principally to the fact that Mars was selected as the first planet to be visited. If the order is reversed and the gravitational field of Venus exploited, the mission can be accomplished with an excess velocity of only 15,000 ft per s.

According to the papers by Dowling *et al.*[20,21], Michael Minovitch did his gravity-propelled trajectory calculations during the summer of 1962 which were then published as JPL TM 312-280 dated 4 March 1963. I was startled to see that Fig. 34 in his report pictures an Earth–Venus–Mars–Earth orbit launched on 27 May 1972 (compared to my own orbit with a launch day on 9 June 1972). They are virtually identical!

## ADDENDUM

When I began the preparation of my lecture for the IAF Congress in Jerusalem, I showed the original lantern slides of the multiple fly-by orbit to the Draper Laboratory librarian. I asked her if it was possible to determine when these slides had been made. "Certainly" was the answer. "We do keep a log, you know." And there indeed it was, after all those years—the proof was in the log!

On 7 February 1961 slides had been made for R. H. Battin described as "6 ORBIT CHARTS (BOTH MARS & VENUS)—APRIL 20, 1966, -SEPT 20, 1966, -SEPT 1, 1967, -AUG 20, 1972, -JAN 25, 1973, -JUNE 18, 1973" and numbered 18831 through 18836. The last three slides illustrate the Earth–Venus–Mars–Earth orbit for the launch date of 9 June 1972. Each slide shows the configuration of the spacecraft and planets for the date cited. In fact, Fig. 26 of the Draper Anniversary volume is the one for 18 June 1973.

The first three slides are for a multiple fly-by orbit with a launch date of 6 February 1966 which also appeared in the Draper Anniversary volume as Fig. 27. It was for the spacecraft and planet configuration of 1 September 1967.

At the end of my presentation in Jerusalem during the 45th IAF Congress in October of 1994, I was told of an article in the February March 1994 issue of *Air & Space Smithsonian* titled "Gravity's Overdrive" which gave a history of the gravity assist principle with only a parenthetical remark noting that MIT had done some work in that area. More recently, in the April/June 1995 issue of *The Planetary Report*, published by The Planetary Society, is an article by Dave Doody of the Jet Propulsion Laboratory titled "Basics of Spaceflight: Gravity Assist." As a part of the introduction he writes: "Astronomers had long known that comets' orbits were altered by encounters with planets, but it was Minovitch who first recognized that the principle could be applied to spacecraft trajectories."—Oh well.

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| 18823 | '/61 | NASA LAUNCH VEHICLES (CHART) | U | R.H. BATTIN | 56-106-4 |
| 18824 | 2/7/61 | IMP ELECTRONICS [HEAD# 480025 - 50TA0] SHEET # 2 | U | A. SPITZAK | 52-156-3- |
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The Editor-in-Chief
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12 February 1997.

Dear Sir,

Subject: PLANETARY FLY-BY ORBITS

I am rather baffled by the article 'Algebraic Compilers and Planetary Fly-By Orbits' by Richard H. Battin in the June 1996 Acta Astronautica, Volume 38, Number 12.

Although I am indeed delighted that the Shuttle was programmed by a High Order Language called HAL, I am surprised by Section 2.3 "Exploiting Gravity During Fly-bys" in which this idea is attributed to Michael Minovitch in 1962. But surely by that date everyone in the business would have been familiar with Derek Lawden's classic paper "Perturbation Manoeuvres" in the JBIS of November 1954. According to Lawden, it was not a new idea even then, as he opens with the words: "A number of writers have suggested that the fuel requirements of a journey between the Earth and the other planets might be reduced by taking advantage of the attractions of various bodies of the solar system...."

The earliest I have discovered, was in a science fiction novel Brigands of the Moon by Ray Cummings in Astounding Stories (March 1930)

> "....We were at this time no more than some sixty-five thousand miles from the moon's surface. The Planetara presently would swing upon her direct course for Mars. There was nothing that would cause passenger comment in this close passing of the moon; normally we used the satellite's attraction to give us additional starting speed."

Sincerely,

Arthur C. Clarke, CBE
Chancellor: International Space University
Patron: Arthur C. Clarke Centre for Modern Technologies

copies: L.J.Carter, BIS
Dr. R.H.Battin ✓
Dr. F. Ordway