KEYNOTE ADDRESS:

IN THE BEGINNING OF GPS

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INTRODUCTION

Good morning. My talk is on the beginning of GPS. I've given this talk several times. Twice it went quite well. But the last time, it was a dead thud, so I'm warning you. A lot of its acceptance level had to do with the listener's age, because when one talks about 1969 to people who weren't born then, the talk has little current meeting.

GPS is a navigation system consisting of two dozen satellites in circular, inclined orbits. Each satellite contains a number of stable clocks. The satellites transmit clock-based synchronized signals continuously, allowing us to have a system unlimited by the number of participants. Further, in not needing interrogation, the user can observe radio silence. Having all the clocks synchronized is a big thing for GPS. At the time the idea of the satellites carrying the clocks was proposed, all the other proposals used interrogated schemes. Receivers detect signals from several satellites simultaneously (> three for x, y, z, and t). From these observations, position and time are calculated.

Where did GPS start? There have certainly been some wild comments about the beginning: (1) "It was developed by the DoD for the U.S. military," which is true; (2) "GPS can trace its heritage to the Navy's Transit program," which is not true; (3) "It began in 1973," while it actually began in 1964. Comment (1) is not especially helpful and comments (2) and (3) are not supported by the documented evidence. One is reminded of the quotation of Thomas Henry Huxley concerning "the slaying of a beautiful hypothesis by an ugly fact." Everything was going fine with these explanations until a fact came along and destroyed them all.

Let's look at some documented evidence. Early in the proposal stage of advanced navigation systems, in 1969, an EASCON meeting was held in Washington. Three different navigation proposals were discussed. (I've given Dr. White copies of these three proposals in case you would like to read them in full.)

LOW-ALTITUDE PROPOSAL

A paper by R. B. Kershner of APL studied the number of satellites necessary at different altitudes to have four-in-view to an observer on the earth's surface. At an altitude of 475 nautical miles (nm), 153 satellites are required. Seventy-eight are required at 1000 nm; 28

are needed at 5000 nm; 18 at 10,000 nm; and 18 at synchronous. Then Dr. Kerschner made a weight and cost comparison between satellites of a constellation at 480 nm and one at synchronous. As seen in the table below, the costs are not greatly different. The APL paper favored the low-altitude proposal.

Weight & Cost Comparison

Altitude	480 nm	Sync.
Tx Power	19 W	150 W
Weight	300 lb.	1100 W
Unit Cost	\$1.5 M	\$11.3 M
Constellation Cost	\$225 M	\$203 M

Conclusion: Costs About Equal

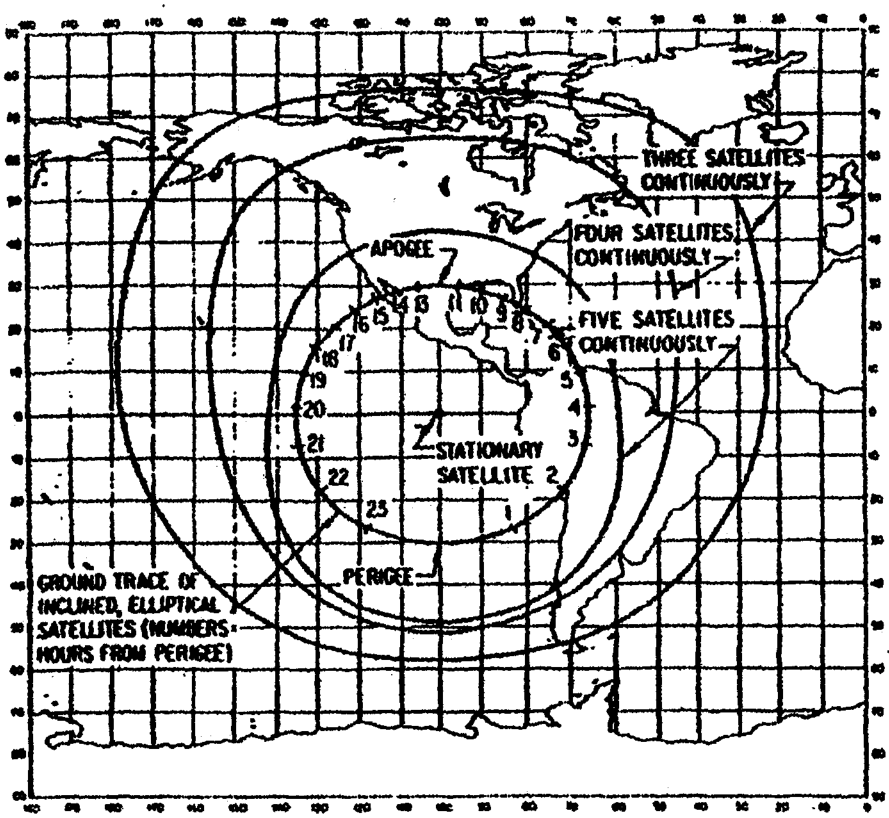
THE AEROSPACE 24-HOUR CONSTELLATION PROPOSAL

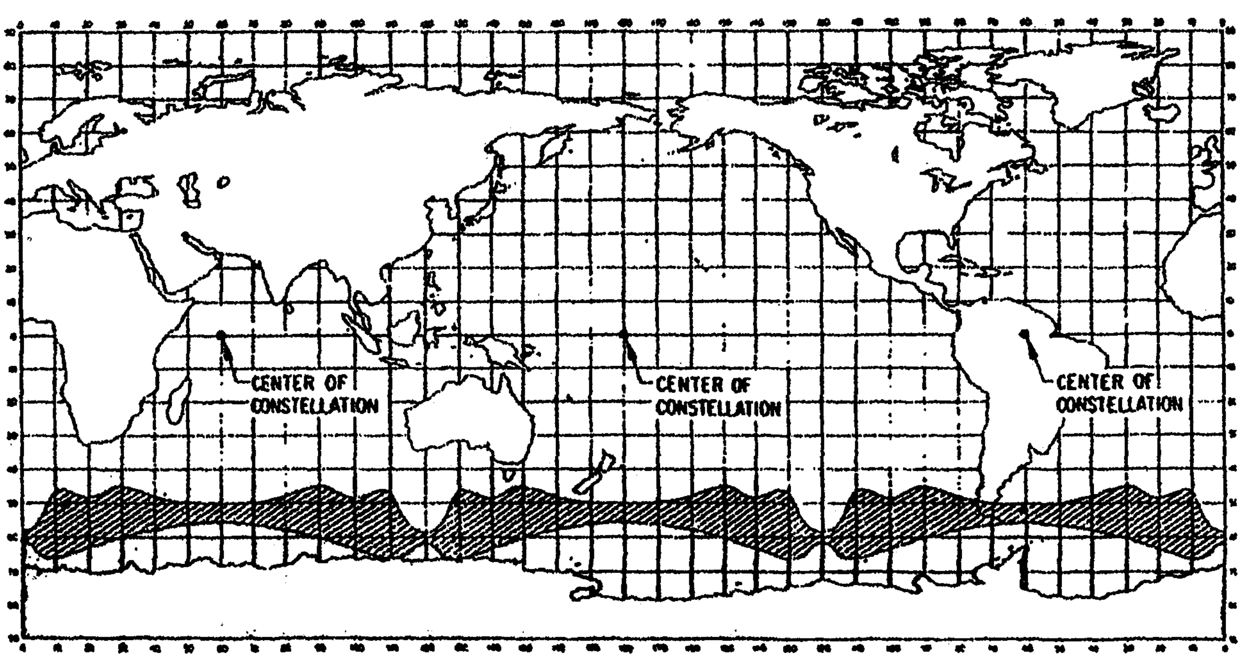
The Aerospace Corporation proposed a 24-hour constellation made up of several choices of sub-constellations and two orbital inclinations. The next figure shows the geometry of one sub-constellation. It consists of a single geostationary satellite with three (or four) satellites in circular ground tracks traveling with the geostationary satellite at the center. The non-geostationary satellites have inclinations of 30 degrees and eccentricities of 0.3 to give the circular ground tracks in the next figure.

The following figure shows the coverege results with three constellations similar to the one described above; for a viewer seeing four to seven satellites for three-dimensional (3D) navigation; for three satellites in view for two-dimensional (2D) navigation; and places near the South Pole with intermittent coverage. The coverage in the North was better because the apogees of the eccentric satellites were to the north. It was a clever system, but its coverage was not strictly global.

WHERE DID GPS START?

So where did GPS start? As I said before, not with the Transit program, though Transit has some similarities. And it started much before 1973. We claim that it can trace its ancestry to the radar "fence" of the Navy Space Surveillance System in 1964, long before some in our audience were born.



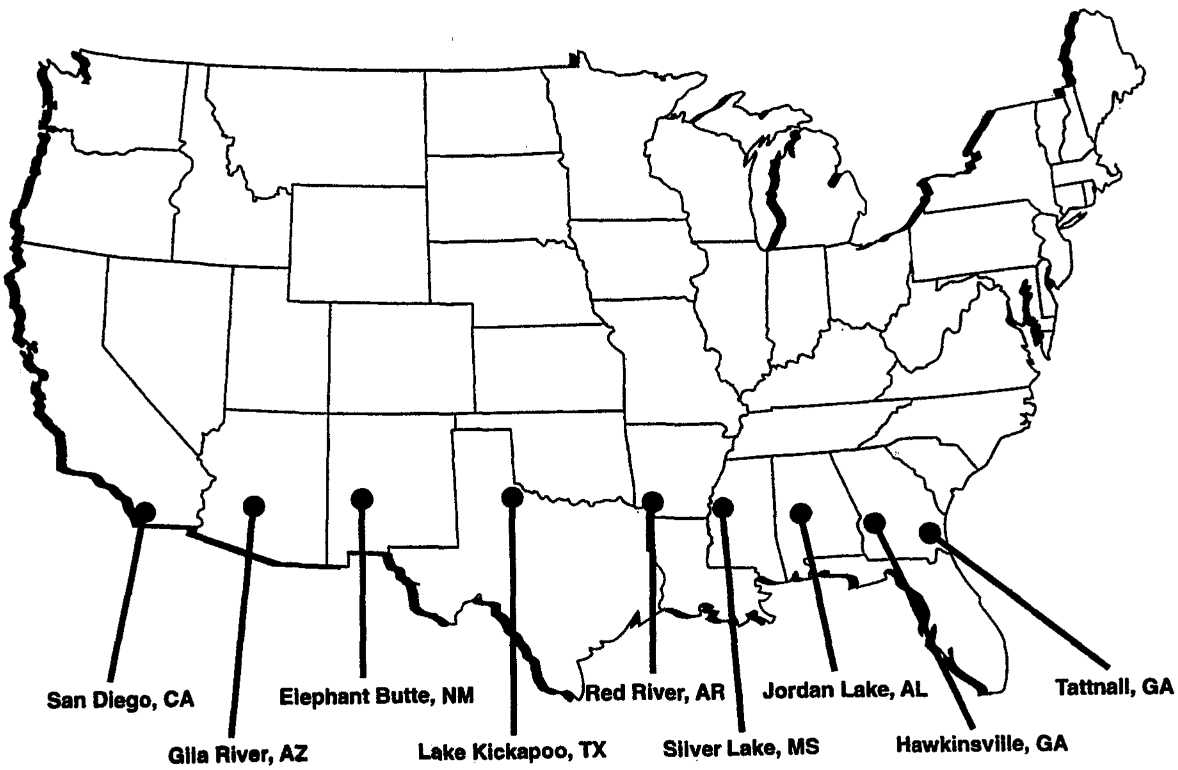


CODE	SATELLITES CONTINUOUSLY VISIBLE	NAVIGATION PROVIDED
	3	2-DIMENSIONS
	4 TO 7	3-DIMENSIONS
	INTERMITTENT COVERAGE	

COVERAGE FOR $i = 30$ deg, $e = 0.30$
MINIMUM ELEVATION ANGLE = 5 deg

THREE CONSTELLATIONS OF FIVE SATELLITES EACH

For a few years in the early 1960s, we operated another fence in addition to the stations shown in the next figure. This second fence was in Southern Texas, with a transmitter near Rio Grande and a receiver near Raymondville. This second fence provided a second look at objects passing vertically through the two systems and permitted the determination of an orbit as soon as the second observation was received. This arrangement was especially valuable for the determination of orbits of multiple pieces.



There are at least two types of radars: pulse radars, which send and receive at one antenna, and continuous wave radars. We worked with the latter, having transmitter and receiver about 100 miles apart. We needed to know the modulation phase of the transmitter at the receiver as it was transmitted. We tried over-the-horizon transmission, which didn't work too well, as the signal was noisy. We tried carrying a cesium-beam clock between the two stations. The idea worked, but it was a continuous job, so we thought, why not put the cesium-beam clock in the satellite?

What else could such a satellite do besides transmit time? We decided it could be used for navigation. We were subjected to criticism because it was an idea looking for an application and not the other way around.

THE MID-ALTITUDE CONSTELLATION

At NRL we investigated a large range of altitudes, from low to synchronous and concentrated mainly on an integral number of ground tracks per day. We favored 8-hour orbits, but had done some work on the 12-hour orbits that GPS chose.

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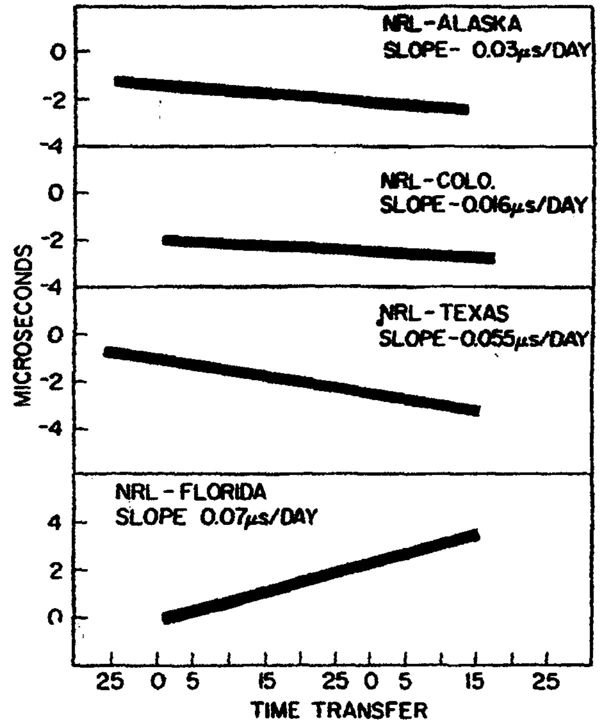
We demonstrated our TIMe navigATION (TIMATION) concept to the Naval Air Systems Command in 1964. As a result, NAVAIR sent us a $35,000 Work Order. The reason the order was so small is that the project manager did not think he could get approval for a larger order.

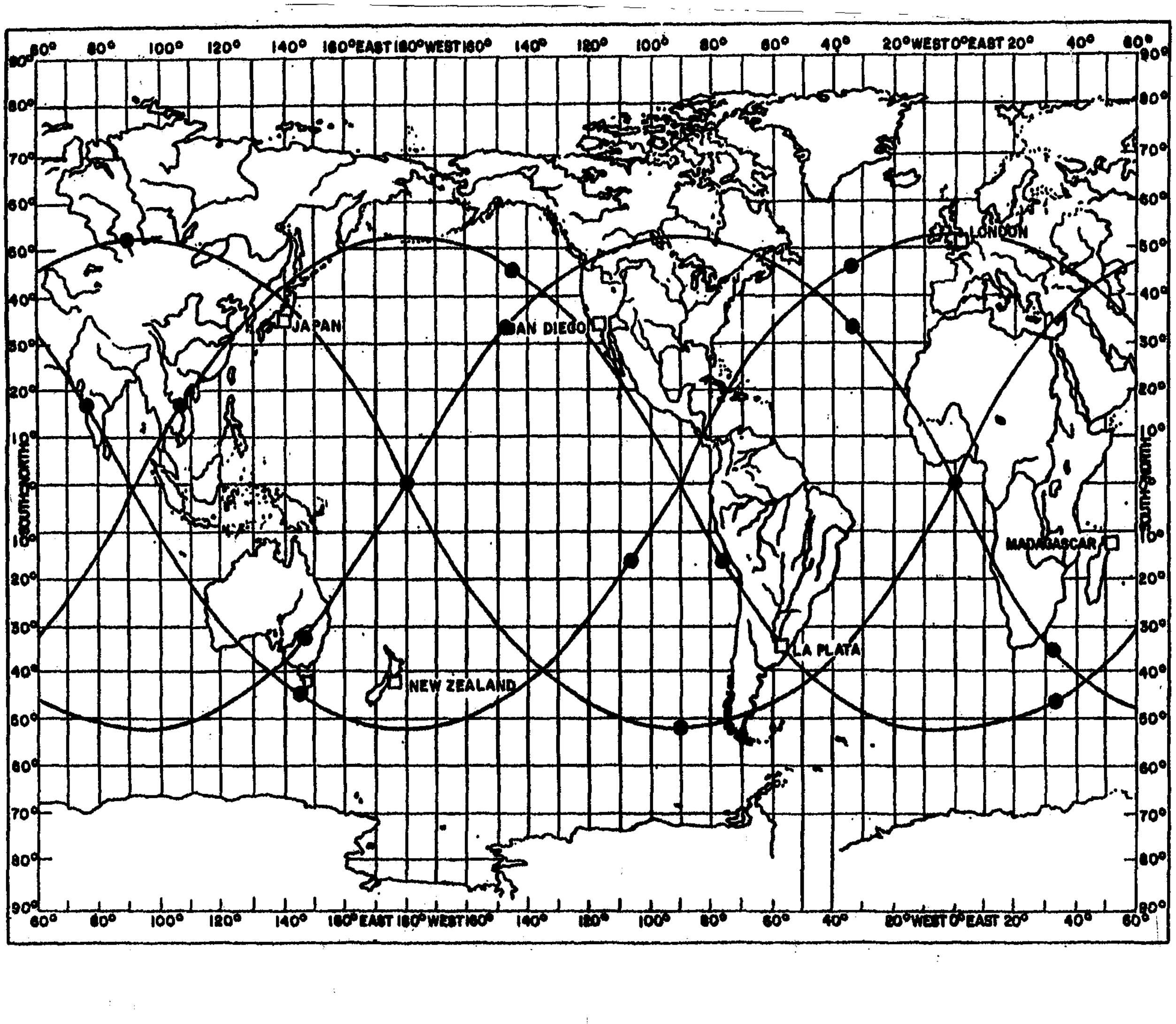
We then demonstrated passive ranging for 2D and 3Dand time which satisfied the navigation needs of aircraft, ships, and ground personnel. In the EASCON paper we favored polar orbits, intermediate altitudes, and circular orbits. We considered quartz and atomic oscillators and obtained the time transfer results in the next figure with the first TIMATION satellite, launched May 31, 1967.

If I had my choice now I think I would go with polar inclinations. We went with 55 degrees because that came out as an optimum under the assumptions used. However, you miss something at that inclination. Unless you are at a low altitude, you see no satellites north (or south) of you. A polar satellite would also be advantageous for keeping the clocks on time.

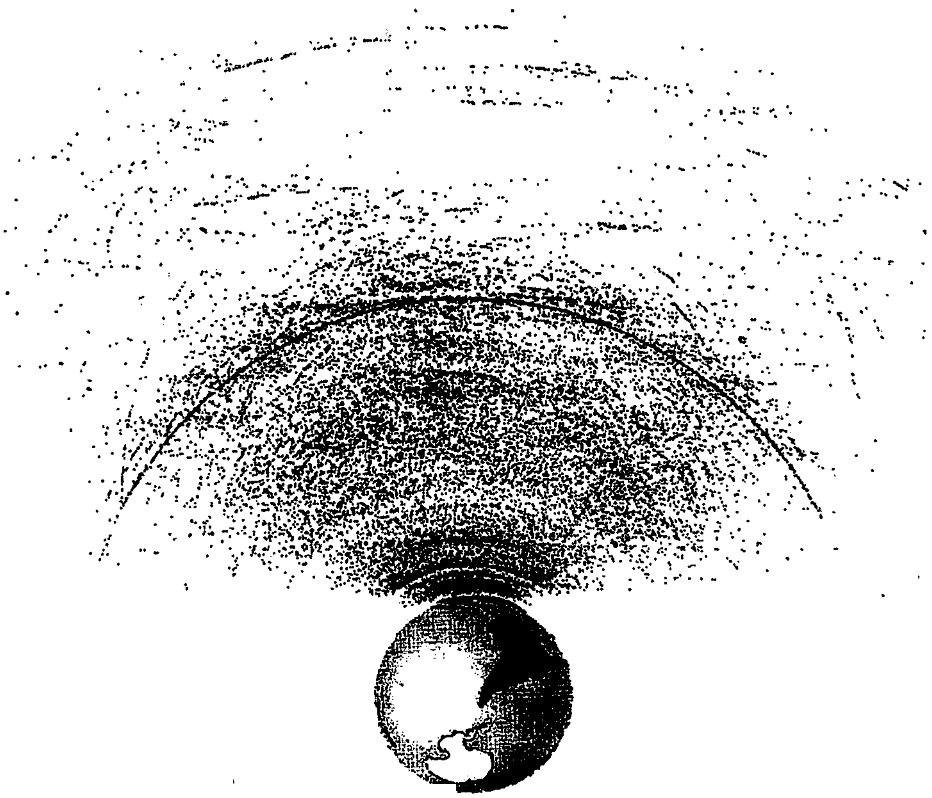
ANOTHER MID-ALTITUDE PROPOSAL

There was another, somewhat similar mid-altitude proposal from General Electric that I must confess that I didn't know about. In a development led by Roy Anderson, it proposed two dozen satellites in 6-hour orbits. It was proposed to NASA and we didn't pay much attention to it. In the following figure are shown its ground tracks and you see it was at 55 degrees, just like GPS. It had both active and passive ranging and accuracies of 0.1 and 1 mile respectively.


NRL-ALASKA
SLOPE- 0.03μs/DAY
NRL-COLO.
SLOPE-0.016μs/DAY
NRL-TEXAS
SLOPE-0.055μs/DAY
NRL-FLORIDA
SLOPE 0.07μs/DAY
MICROSECONDS
TIME TRANSFER


JAPAN
SAN DIEGO
LONDON
MADAGASCAR
LA PLATA
NEW ZEALAND
160°EAST 180°WEST 160°
20°WEST 0°EAST 20°
NORTH
SOUTH

The next figure shows observations seen from the present space surveillance fence. The arc about 12,000 miles from the earth represents the observations of the GLONASS satellites.



THE WINNER

Why did the mid-altitude proposal win? One could say because it was cheaper, more accurate, truly worldwide, and required fewer ground stations. The chart above relates the different proposals to the final design of GPS. One could say that since the GPS came from the NRL proposal, it naturally is most like the NRL TIMATION proposal. The next table compares the various proposals, showing which are most like the final choices (X) for GPS.

Proposal	Circular Orbit	Medium Altitude	Global Coverage	Atomic Clocks
GE	X	X	X	O
Aerospace (621B)	O	O	O	O
APL	X	O	X	O
NRL	X	X	X	X

Since the relevant patent may be of some interest, I've included a copy of the first page.

United States Patent [19]

Easton

[11] **3,789,409**

[45] **Jan. 29, 1974**

[54] **NAVIGATION SYSTEM USING SATELLITES AND PASSIVE RANGING TECHNIQUES**

[76] Inventor: **Roger L. Easton, 7704 Oxon Hill Rd., Oxon Hill, Md. 20021**

[22] Filed: **Oct. 8, 1970**

[21] Appl. No.: **79,307**

[52] **U.S. Cl.** .... **343/112 R, 343/100 ST**, 343/112 D

[51] **Int. Cl.** **G01s 5/14, G01s** 11/00

[58] **Field of Search** .... 343/112 D, 112 R, 100 ST

[56] **References Cited**

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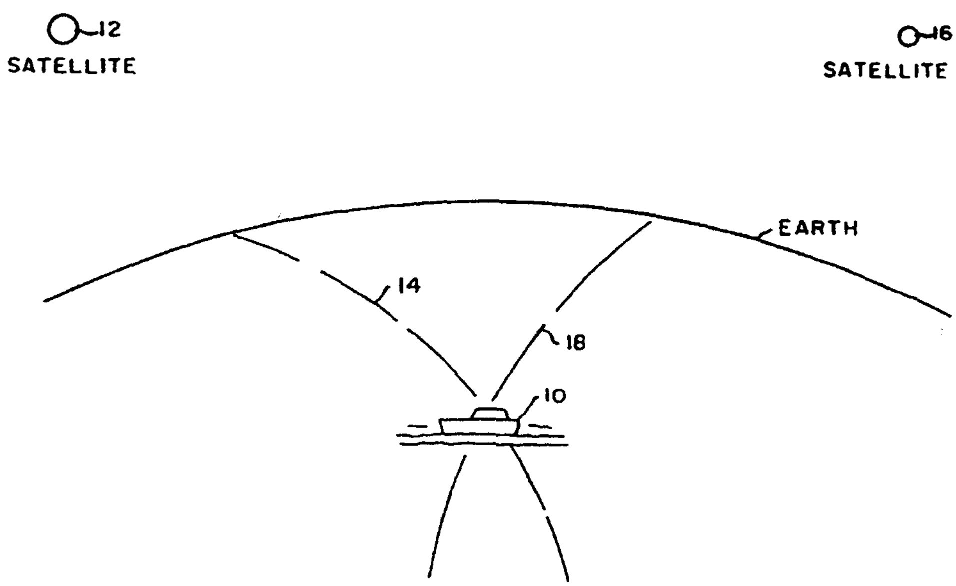
Primary Examiner—Richard A. Farley
Assistant Examiner—Richard E. Berger
Attorney, Agent, or Firm—R. S. Sciascia; Arthur L. Branning; J. G. Murray

[57] **ABSTRACT**

A navigation system wherein the navigator's location is obtained by determining the navigator's distance (or range) from one or more satellites of known location. Each satellite transmits multifrequency signals that are derived from a stable oscillator which is phase synchronized with the navigator's equipment that produces similar multifrequency signals. Phase comparison between the signals received from the satellites and the locally produced signals indicates both the distance between the navigator and the satellites and the navigator's location. In determining his location, the presence of the navigator is not revealed since no interrogatory transmission by him is required.

6 Claims, 3 Drawing Figures



THE SECOND PART

This talk was made in two parts. You've have heard the first or technical part. The second part consists of a number of quotations. "The purpose of poetry is to persuade, fool, or compel God into speaking" is a favorite from Howard Nemerov. It is especially pertinent if you feel that some engineering approaches a class of poetry.

Then there are religious quotes coming from technical people. There's the famous one from Einstein: "Der Herrgott is subtle but not malicious." Two others, "Doing physics was walking the path of God" and "Doing physics was wrestling with the Champ," are by I. I. Rabi, who, of course, had much to do with atomic clocks.

John M. Zinman said, "Modern science is a successful social invention for acquiring, not truth, but reliable knowledge." I think Robert Frost's quote, "Two roads diverged in a wood and I took the one less travelled by," is perhaps a good way of looking at what we do in experimental fields. Of course, Frost is sort of a permanent poet laureate up New Hampshire and Vermont. He lived in both states, but was born in California and named for General Lee.

Some developments that were essential to GPS are small atomic clocks and integrated circuits. I was glad to see Mr. Fruehauf here. He was in on the very small atomic clocks, which we flew in satellites. Later, we went to Mr. Kern's cesium clocks.

I want to say something concerning awards: "Love of praise is, I believe, common to all men and whether it be a frailty or a virtue, I plead no exception from its fascination" (Capt. J. Eads, 1874). I like this one: "All anybody needs to know about awards is that Mozart never received one" (Henry Mitchell).

If you look at the awards mentioned in the World Almanac or any other almanac, you will see that there are almost none that apply to engineering. We know of the Pulitzer and Nobel prizes, but there are at least 29 entire categories of other awards. You won't find many scientific awards. When I was young, the Collier Award for Advances in Aviation was generally known. It's not well known now, nor is the oldest U.S. award, the Magellanic Premium (1786). So if you want an award, go into a field like entertainment, sports, or writing, and stay away from fields that change the world, like engineering.

In spite of what I have said about awards, I appreciate the one given me today. It's a beautiful clock. I will try to place it in its proper place. Thank you very much.

Questions and Answers

BRUCE MONTGOMERY (Syntonics, LLC): Who were the chaps at General Electric who were so prescient back in 1964? They got it pretty close to right.

ROGER EASTON: That was Roy Anderson. I got to know him very well since, and he's very impressive in this field.

HUGO FRUEHAUF (Zyfer, Inc.): The irony was that GE dropped out of the satellite bis when it finally got to the satellite award. Even though they were so ahead of the game.

EASTON: You are saying they dropped out?

FRUEHAUF: Yes, the final bidders were Rockwell and RCA at the time, and General Electric ended up bowing out of the satellite race, which was kind of ironic.

EASTON: Then they ended up buying RCA, right?

FRUEHAUF: Right.