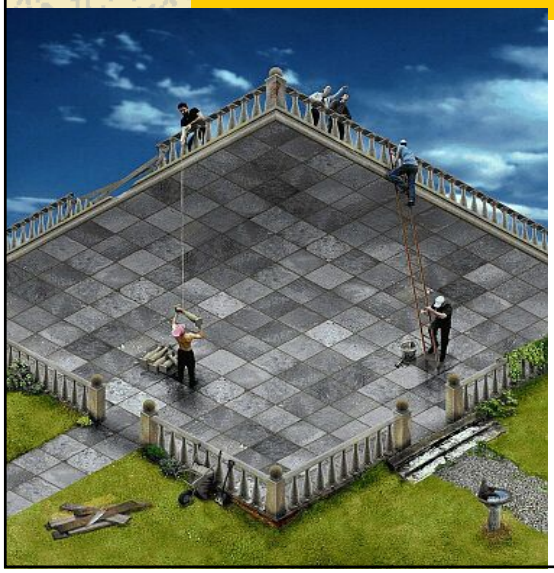
Building the Geodetic VLBI Network

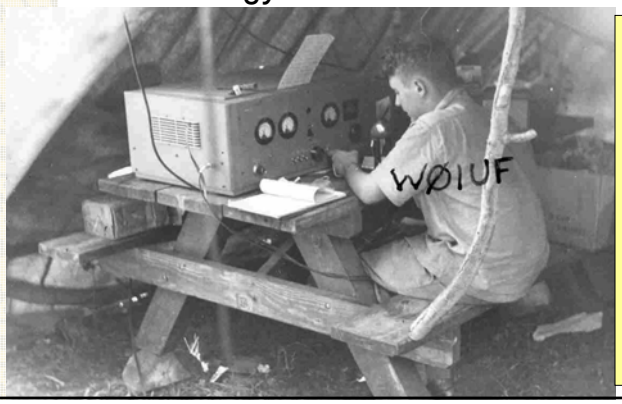


Some Personal Recollections of Tom Clark

IAA -- St. Petersburg
10 Feb 2005

A few words about me

I grew up in a small town in Southern Colorado.
At a very young age, I became interested in Science and Technology and became a Radio Amateur.



Amateur Calls:
WØIUF,
W4JBL,
WA3LND,
G4UTL,
W3IWI,
CE3/W3IWI,
SM6/W3IWI,
LA/W3IWI
JW/W3IWI,
JA/W3IWI,
UA/W3IWI,
XE/W3IWI,
etc

A few more words about me

I attended the University of Colorado in Boulder and did my Ph.D. dissertation by building a very large 10 MHz Radio Telescope on a mesa north of Boulder.



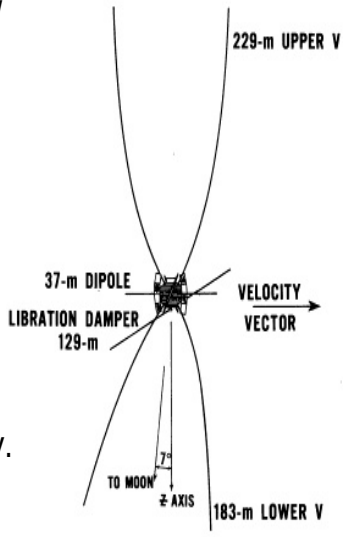
A few more words about me

From Boulder, I spent 2 years at NASA/ Marshall in Alabama working as Werner von Braun's Solar Physicist.

In 1968, I moved to NASA/Goddard to work on VLF Radio Astronomy with RAE-1 (Explorer 38) and RAE-2 (Explorer 49) satellites.

At about the same time, VLBI and Pulsars caught my interest.

And in 1969, I joined the University of Maryland Physics&Astronomy faculty.



Getting NASA/Goddard interested in VLBI

- Goddard had an R&D program with Harry Peters developing Hydrogen Maser frequency standards.
- Goddard was "home base" for satellite tracking networks (Manned & Unmanned, but not DSN).
- Goddard had large general-purpose computers.
- Goddard encouraged its scientific staff to work on independent projects of interest.
- The U.MD Grad Students were an inexhaustible source for slave labor.

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Getting Bob Coates interested

To: Dr. R. J. Coates February 27, 1969

From: Dr. T. A. Clark

Subject: Maser Long Baseline Interferometry

This memo is written to inform you of the status of out Very Long Baseline (VLB) Interferometry experiments and to request your assistance and support for same.

1. Current Status

As you know, Tom McGunigal and Harry Peters have been kind enough to refurbish one of the Varian H-10 hydrogen masers which is now in operation at VLB terminal with the 140' dish at the National Radio Astronomy Observatory at Greenbank, W. Va. This maser has been routinely operated for several VLB runs, most recently at 6 cm in an experiment involving the 85' dish at Onsala, Sweden and the new 130' dish at the California Institute of Technology (CIT) Owens Vally Observatory.

We have also begun assisting NRAO in the data processing area on some of their VLB runs. We have adapted their analysis programs to the IBM 360-91 and find that where it used to take them more than an hour to process a three minute pair of data tapes, we accomplish the same in about 5 minutes.

The two individuals in our group who have been most interested in pursuing VLB experiments are Larry Brown and myself. We too a brief trip to NRAO last month to witness the NRAO-CIT-Sweden runs. We also spent considerable time with Dr. Ken Kellerman and Dr Barry Clark (no relation) about our involvement. It became quite clear that they appreciated the maser being loaned to them and were eager to encourage our performing some new observations.

Getting Bob Coates interested - 2

2. Planned Programs

In these discussions it became apparent that there were three areas of mutual interest that require the use of masers:

(a) Rotation Synthesis mapping of small diameter discrete radio sources.

In these observations we will make use of the fact that as the earth rotates, the interferometer configuration viewed from the source changes. By properly connecting the data, two dimensional mapping with angular resolution ~0.001 seconds of arc can be made. Such questions as "Are the time variable emissions from quasi-stellar sources ("smoke puffs") coming from the same location within the source?" and "Are quasi-stellar sources and Seyfert galaxy nuclei spherical or elongated?" can be answered by such observations. Such questions are fundamentally important to describing the physical nature of such sources.

(b) Position measurements on discrete radio sources.

These observations are quite related to those described above and we hope to measure positions to similar accuracies -- ~0.001 seconds of arc. These measurements might best be called "Radio Astrometry". Since optical positions are not known to comparable accuracy, we will be forced in essence to redefine the coordinate system for the celestial sphere. With such observations we would hope to provide many useful astronomical observations, including a test of the Einstein General Relativity prediction of the bending of light (radio) wave passing near a massive body (the sun). In addition it should be possible to measure distances on the earth to a few cm (continental drifts), the length of the day to 10^{-4} seconds, Precession and nutation to small fractions of a second or arc, etc. The synthesis and position measurements will be made at decimetric wavelengths and require masers to provide phase coherence over many hours of observing.

(c) Observations of small diameter discrete sources at ~1 cm.

In these observations we would hope to extend the existing observations to higher resolution by getting more wavelengths in our gasoline [*sic*!!]. These observations will also help determine the variation of source size with wavelength, which is related to the point at which the source becomes optically thick. These observations will require masers to preserve phase to better than a radian over each three minute observing cycle.

Getting Bob Coates interested -3

3. Scheduling and Logistics

It would appear right now that we would like to try some initial maser VLB runs in late July, 1969. Observing time can be scheduled on the NRAO 140' dish then and Dr. Kellerman will be at CIT for the summer and has indicated that 130' dish time can be arranged. We understand from talking with Harry that the plans for the new NASA masers call for the shipment of one unit to Mojave sometime in the summer for testing in the MSFN station. We would like to try to "waylay" this unit for use at Owens Vally in July. We would plan on about two weeks of observing time plus a week or two for transportation, set-up, etc., so the Mojave test would suffer no more than a month of delay. In this period we would try both phase-stable mapping and some 1 cm observations. If these tests go successfully, we would also hope to try observations of the sources 3C273 and 3C279 in October. These sources are particularly well suited to the General relativity experiment.

Since it is necessary for us to schedule three major items (2 dishes plus the maser), our logistical problems are messy. We would appreciate your cooperation in making arrangements.

4. Longer Range Plans.

The VLB field has barely been scratched and we stand at the threshold of some major breakthroughs. We would like to suggest that if the MSFN tests are successful and the masers are deployed to the 85' dish station, that NASA should plan to utilize these facilities for VLB Radio Astronomy observations. If the tests should prove that the masers are not needed in the MSFN, we would like to put in our bid for a pair of the new masers. In either case, we feel that our involvement in these programs will be scientifically profitable, and should be pursued.

/s/ Thomas A. Clark

The Five Eras of VLBI

- 1967-1979: The Mark-1 System
  - ½" Computer Tape, 800 BPI, 720 kb/s, 3 Mins/tape
  - Mainframe Computer is Correlator: IBM 360-50 / -75 / -91 / -95
  - Our Correlator phase model on IBM 360's was very accurate
  - Bandwidth Synthesis was developed

    General Relativity Tests, Baselines, UT, Polar Motion, Closure Phase, Superluminal 3C279 v≈10c, Time Synchronization
  - Meter Wavelength VLBI

    Source Fluxes & Structure
  - Pulsar VLBI

    Crab Nebula

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The Mark-1 Era
The East Coast VLBI "Family"

Program introduced many students to VLBI

- MIT & Haystack (Irwin Shapiro, Chuck Counselman, Alan Rogers)

Allen Whitney	**Hans Hinteregger**
Curt Knight	**Doug Robertson**
Bob Preston	**Marty Slade**
Roger Cappallo	**Tom Herring**
Jim Davis	**Brian Corey (postdoc)**

- NASA/Goddard & U.MD (Tom Clark & Bill Erickson)

Nancy Vandenberg	**George Resch**
Chopo Ma	**Kate Hutton**
Tom Kuiper	**George Kaplan**
Will Cronyn	**Gerry Marandino**

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The Mark-1 Pulsar & Meter Wavelength VLBI



- Telescopes = 91M @ Greenbank + 45M @ Sugar Grove + 305M @ Arecibo
- Frequencies = 74, 111, 121, 145, 196 MHz
- Thesis Topics for Nancy Vandenberg & George Resch

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In addition to the 91m, our other VLBI Programs used NRAO's 43m for Pulsar, Source Structure & Geodesy, and the Interferometer for General Relativity.


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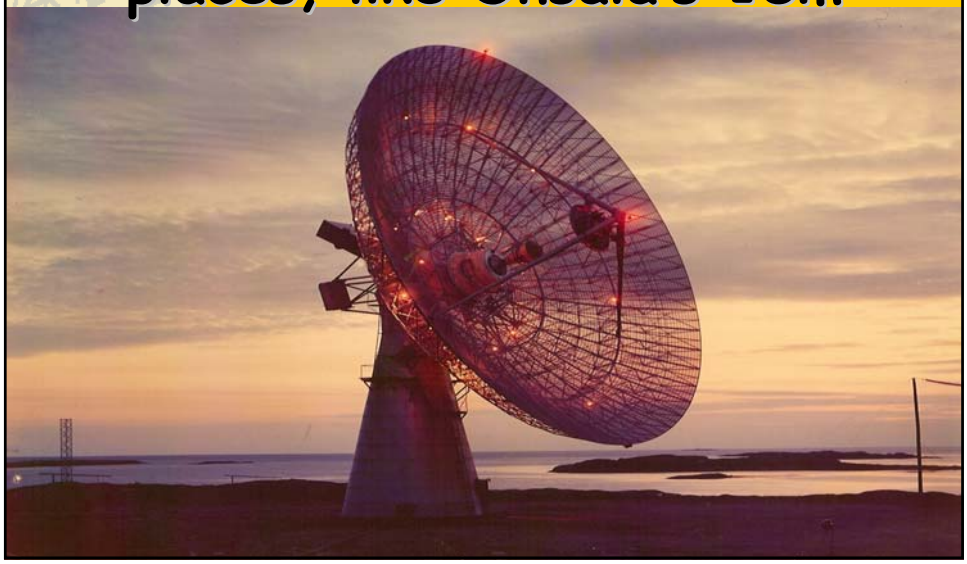
Some Student Activities during months spent at NRAO

Mark-1 used MANY Tapes!

10,000+ during "Octoberfest 1972"

Visiting telescopes in interesting places, like Onsala's 18m



Nancy's thesis proved that the compact continuum source in the Crab Nebula at 100-200 MHz was within a fraction of an arc-second of the Crab Nebula Pulsar !

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The Mark-2 Era

- 1972-1980: The Mark-2 System
  - 4 Mb/sec data rate, 2 MHz bandwidth
  - Based on commercial Video Tape Recorders
    - 2 inch AMPEX
    - VHS
  - Extensive use by astronomical community
  - The 'East Coast Mafia' (NASA/GSFC, MIT, Haystack) did NOT use Mark-2 very much because the corellator did not give good phase data and reproducible results.

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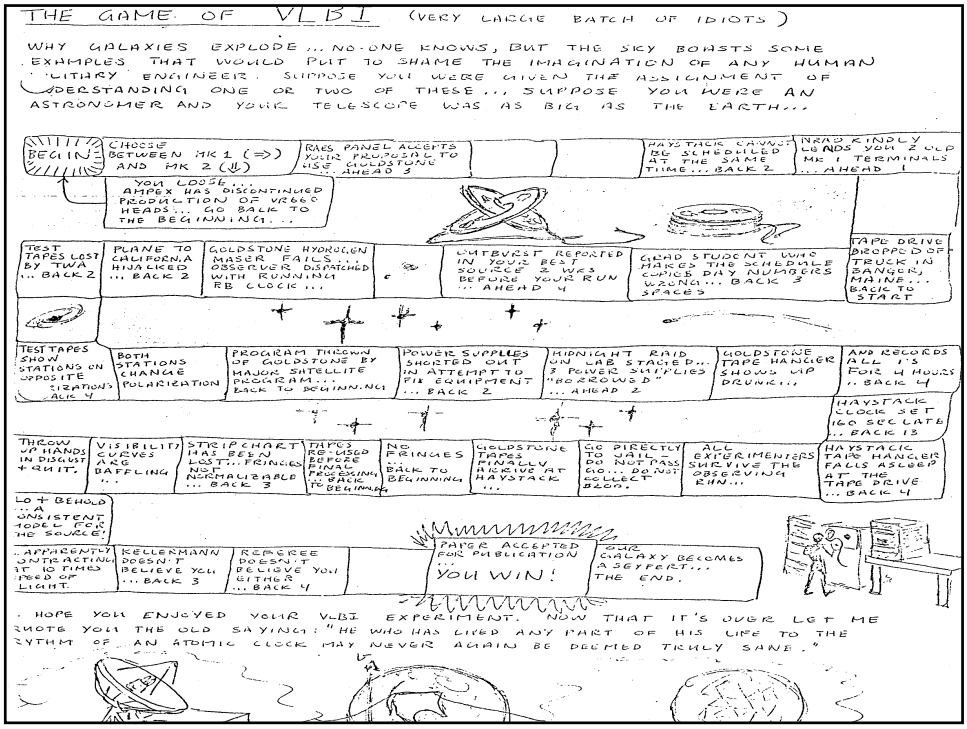
THE GANG OF FOUR



1975 – 81: PPME & CDP

- PPME = Pacific Plate Motion Experiment: A Joint program between NASA & Japanese CRL.
- CDP = NASA's Crustal Dynamics Project
  - Experimental Test of Plate Tectonics and the 1978 Minster-Jordan Plate Motion Model
  - Regional Deformation along San Andreas Fault
  - UT1, Polar Motion, Precession, Nutation
  - Techniques = VLBI and Satellite Laser Ranging
- Provided significant funding for development of Mark-3 Data Terminal and VLBI stations. $ $ $

20

Early CDP: The Mark-3 Era

- Flexible data terminal with supporting bandwidths up to 224 Mb/sec (112 MHz bandwidth) using 1 inch tape and 28 channel instrumentation recorders.
  - Up to 28 tape tracks = channels
  - Parallel recording on all channels
  - Computer Control of Data Acquisition
  - Dedicated Correlators
- Joint Development between Haystack+NASA & NRAO.
- Initial tests in 1977, Operational in 1980

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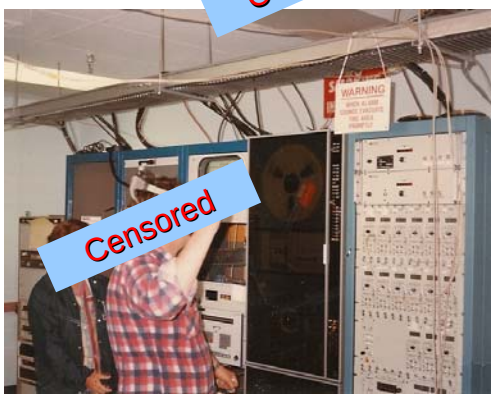
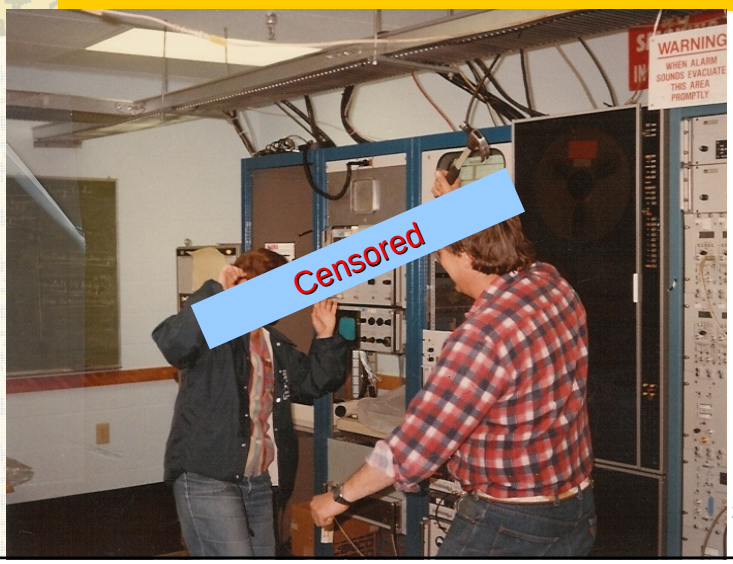
Mark-3 in 1980

Early Testing at OVRO and [illegible]O



Tape Recorders have always been a problem !

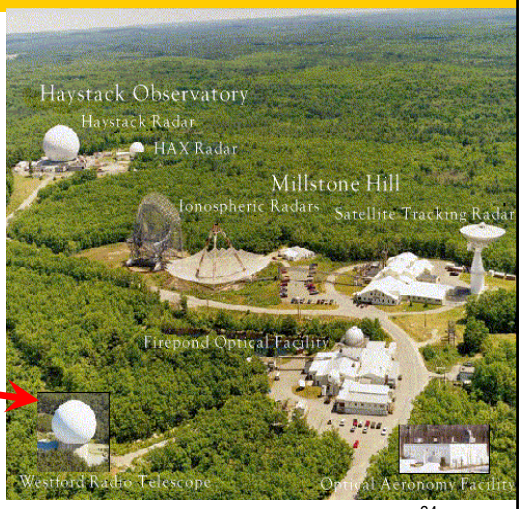
No, it was YOUR fault !



23

1980/81: A Real Geodesy Program

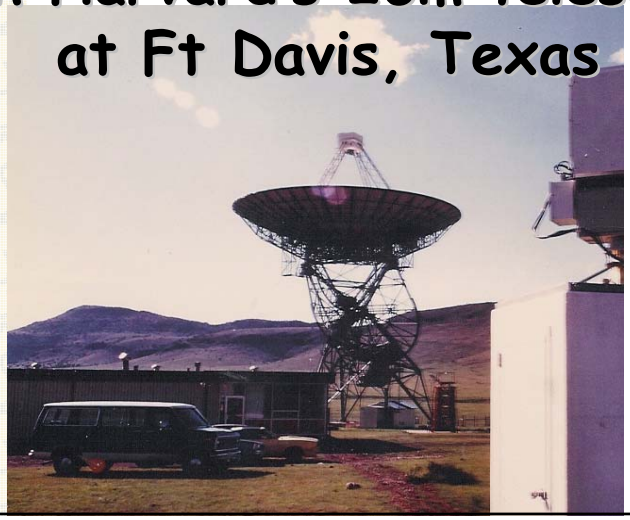
- NASA joins with NGS and Haystack to develop the first Dedicated Geodetic VLBI station, the 18m Westford Radio Telescope
- This was the beginning of the Polaris network



24

Westford's Dedication Ceremony: 1981

1981: POLARIS augmented with Harvard's 26m telescope at Ft Davis, Texas



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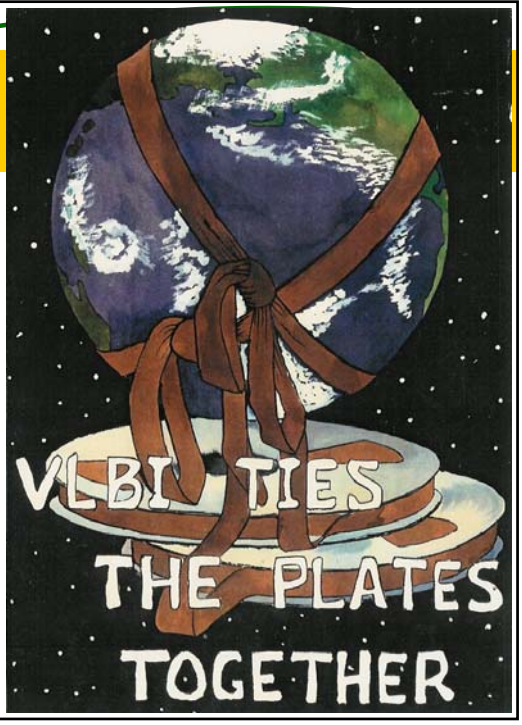
The CDP in 1981

NASA's CDP & NGS's Polaris projects helped to define the VLBI & SLR observing programs & technical developments for the decade of the 80's

Mark-3 VLBI Gets it own Tee Shirt, courtesy of Kate Hutton.



CDP & Polaris: 1981 - 87

- Dedicated geodetic VLBI facilities added at Fort Davis, Goldstone (Mojave), Wettzell, Hawaii & Fairbanks
- Other facilities used for geodesy included DSN, Onsala, OVRO, Greenbank, Bonn & Kashima.
- Mobile VLBI stations used in California (San Andreas Fault) & Alaska (NOAM/PCFC boundary).
- GPS begins to be used for geodesy.

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Mojave (Goldstone): 1983

30

Fairbanks Gets Cryogenics: 1984

VLBI as seen by the public

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VLBI as seen by the public

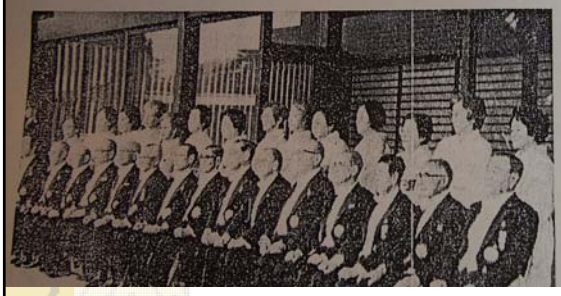
The Japan Times Thursday, November 7, 1985 Page 3

Hawaii Moving Closer to Japan, Study Finds

The Hawaiian and the Marshall Islands, both in the North Pacific Ocean, are moving closer to the Japanese archipelago at a rate of 4 to 8 cm a year, while the distance between Japan and the North American continent hardly changes at all, a Japan-U.S. joint study has revealed.

The study, the first of its kind, to monitor moves of the Pacific plates, illustrates very well the so-called "plate technonics" theory a spokesman of the Japanese team said.

The theory says that the oceanic floor, composed of several rigid plates, slides at rates from one to several centimeters a year. The movements are believed to be caused by eruptions of mid-ocean undersea volcanoes which push up the lava in the Earth's mantle, spread it laterally to either side, and then create a new crust or oceanic plate pushing the old plates aside.



The study has been conducted by the Radio Wave Research Laboratory of the Posts and Telecommunications Ministry and the U.S. National Aeronautics and Space Administration (NASA) using a method called very long baseline interferometer (VLBI.)

The VLBI consists of monitoring of a radio wave from a quasar more than 1 billion light years distant from Earth with antennas set up at a number of different locations on the globe and measuring the differences in the times of arrival of the wave at the different antennas, the spokesman said.

By this method, the scientists can measure the distances between the different antennas to fine accuracy.

In the study, the Japanese and American scientists installed the antennas at Kashima in Ibaraki Prefecture, on Kwajalein Island in the Marshall Islands, on Kauai Island in Hawaii, Fairbanks in Alaska and Mojave in California.

The distances between Kashima and four other locations were monitored in both 1984 and 1985, and the test results showed that the distance between Kashima and Kwajalein shortened by 8 cm in the one-year period, the spokesman said.

The distance between Kashima and Kauai shrank 4 cm in the same period, he said.

However, little difference was confirmed among the data obtained at Kashima and the site in the North American continent, he said.

AGU

June 1987

In 1987, CDP & VLBI people presented a number of papers at the Spring AGU meeting.

Strong support for science community !!

Geophysics Smorgasbord Was Spread in Baltimore

Geophysicists specializing in everything from atmospheric science to volcanology converged on Baltimore for the spring meeting of the American Geophysical Union held 18 to 21 May. The range of fare was huge, but here is a sampler: two high-energy phenomena—nuclear testing and the less frequent cratering by large impacts—and an imperceptibly slow process—the motion of the tectonic plates.

Direct Measurements Confirm Plate Tectonics

For any doubting Thomases out there, the final word is in—plate tectonics is real, the continents do drift the way the theory predicts. Faint models of Earth and variations on plate tectonics, such as an expanding Earth, can be put to rest.

The deciding evidence comes from the precise measurement of distances across plate boundaries made by the technique of very long baseline interferometry (VLBI). At the meeting James Ryan of Goddard Space Flight Center in Greenbelt, Maryland, reported the latest VLBI results from the Crustal Dynamics Project operated by the National Aeronautics and Space Administration. In a subprogram of the project called the Great Alaska-Pacific Experiment (GAPE), large radio antennas in western North America, the central Pacific, and Japan were used to record radio noise from immensely distant quasars that act as stationary reference points. The millisecond differences in the arrival times of the same signals at different sites yielded the distance between receivers.

Thanks to the relatively high speed of the Pacific plate, there is no doubt that real plate motion has been detected. After only 3 years of observation, Ryan noted, the calculated shortening of the distance between Hawaii and a site near Fairbanks in central Alaska appears to be 52.3 ± 5.5 millimeters per year. Hawaii is moving toward Japan at a rate of 83 ± 8 millimeters per year.

Although researchers have been trying for years to determine how much larger than such formal errors the true error is, no one doubts that the observed rapid movement far exceeds any possible error. In addition, the GAPE sites are moving much the way plate tectonics predicted. Hawaii, for example, is moving 83 millimeters per year to the northwest (a course of 322° if Fairbanks is considered stationary. Previous analyses of the magnetic stripping of the ocean floor and other geologic evidence showed that in the geologic past Hawaii had moved at 90 millimeters per year to the northwest (320°). Around the Pacific, observed rates are tending to be a few millimeters per year less than the geologic rate, but so far GAPE researchers do not consider the differences significant. A few more years of observation will be required before any real differences might be discerned.

In the Atlantic things are much slower moving, but VLBI researchers, despite their conservative nature, are conceding that they have probably detected plate motion there as well. A consortium of Crustal Dynamics Project researchers from one European and six U.S. institutions recently stated in print that they have measured the opening rate between North America and Europe as 17 millimeters per year. The geologic rate is also 17 millimeters per year. After a considerable analysis effort, they placed an upper limit of 10 millimeters per year on the rate's true uncertainty. According to consortium member Thomas Herring of the Harvard-Smithsonian Center for Astrophysics, that is "very strong evidence of plate motion."

On the move. *This VLBI antenna on the island of Kauai in Hawaii is moving 8 centimeter per year toward Japan.*

RESEARCH NEWS 1420

These VLBI results would seem to eliminate once and for all alternatives to the broad scheme of moving plates that was widely accepted almost 20 years ago. Plate tectonics accommodates the measured opening of the Atlantic with sea-floor spreading at the Mid-Atlantic Ridge, and the encounter between the Pacific plate and the largely continental North American and Eurasian plates naturally leads to the predicted subduction of the Pacific plate along the northwest Pacific rim. The alternatives generally preclude sea-floor spreading, subduction, or both. The expanding Earth hypothesis, for example, allows for sea-floor spreading that accommodates the increasing surface area of the globe but predicts that there is no subduction. But then, the dissenters have been nothing if not resourceful. There may yet be new alternatives.

Do Tectonic Plates Drive Themselves?

Now that the drift of continents and the plates that carry them has been measured directly, it would be nice to know what makes it all go. According to recent results from one computer model of plate driving forces, the plates may provide their own motive force.

Donna Jurdy of Northwestern University, Michael Stefanick of Science Systems and Applications, Inc., in Seabrook, Maryland, and John Harper of Victoria University of Wellington, New Zealand, reported that the pull of ocean plate edges sinking into the mantle may provide sufficient force. In their model, the positions, sizes, and velocities of plates in the past are reconstructed from the magnetic record of the sea floor. Jurdy and her colleagues then assumed that only the drag at the base of plates, which can be calculated from the reconstructions, resists plate motion. Recent results from the scientific drill hole at Cajon Pass near the San Andreas fault support the absence of large amounts of drag at plate-plate boundaries.

To balance plate drag, they chose the pull of oceanic plates that have cooled so much since their formation that they are dense enough to sink into the mantle at deep-sea trenches. This slab pull, the magnitude of which depends on the length of the subduction zone and rate of subduction in the reconstruction, plus a proportionally smaller trench suction force induced by subduction were the only forces driving the plates.

When the slab weights of the model were allowed to adjust themselves until the best balance was achieved, plate drag and subduction driving forces achieved an excellent

1420

1984 - 1990: - GAPE - The Great Alaska & Pacific Experiment

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Results 1984 - 1990

- Confirmed most features of Minster-Jordan Tectonic model, but with ~10% difference in some velocities, especially Pacific - N.America.
- Agreement with new NUVEL model very close.
- Earthquakes “detected” in Alaska and California.
- VLBI LOD shows close agreement with integrated winds from global climate models.
- Free-core nutation of the Earth’s core detected– Annual Period with amplitude of ~ 2 milliarcseconds.
- Etcetera!

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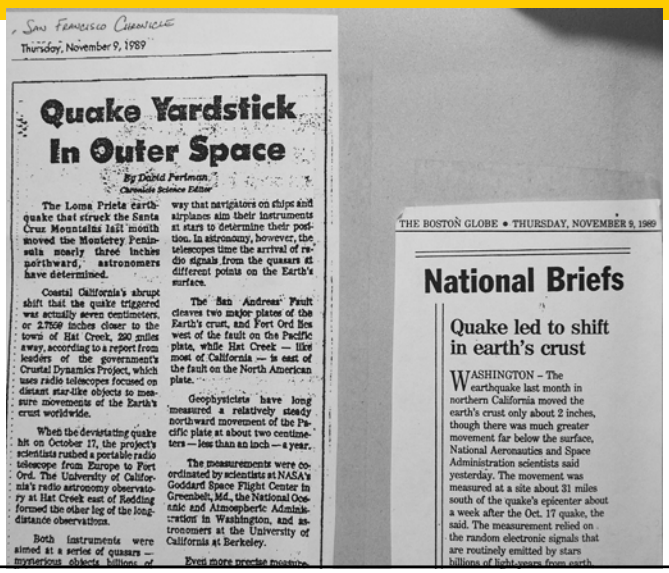
The 1989 Loma Prieta Earthquake

VLBI answers were available BEFORE data from GPS!



San Francisco Chronicle
Thursday, November 9, 1989

Quake Yardstick In Outer Space

By David Perlman
Chronicle Science Editor

The Loma Prieta earthquake that struck the Santa Cruz Mountains last month moved the Monterey Peninsula nearly three inches northward, astronomers have determined.

Coastal California's abrupt shift that the quake triggered was actually seven centimeters, or 2.7559 inches closer to the town of Hat Creek, 290 miles away, according to a report from leaders of the government's Crustal Dynamics Project, which uses radio telescopes focused on distant star-like objects to measure movements of the Earth's crust worldwide.

When the devastating quake hit on October 17, the project's scientists rushed a portable radio telescope from Europe to Fort Ord. The University of California's radio astronomy observatory at Hat Creek east of Redding formed the other leg of the long-distance observations.

Both instruments were aimed at a series of quasars — mysterious objects billions of

way that navigators on ships and airplanes aim their instruments at stars to determine their position. In astronomy, however, the telescopes time the arrival of radio signals from the quasars at different points on the Earth's surface.

The San Andreas Fault cleaves two major plates of the Earth's crust, and Fort Ord lies west of the fault on the Pacific plate, while Hat Creek — like most of California — is east of the fault on the North American plate.

Geophysicists have long measured a relatively steady northward movement of the Pacific plate at about two centimeters — less than an inch — a year.

The measurements were coordinated by scientists at NASA's Goddard Space Flight Center in Greenbelt, Md., the National Oceanic and Atmospheric Administration in Washington, and astronomers at the University of California at Berkeley.

Even more precise measure-

THE BOSTON GLOBE • THURSDAY, NOVEMBER 9, 1989

National Briefs

Quake led to shift in earth's crust

WASHINGTON – The earthquake last month in northern California moved the earth's crust only about 2 inches, though there was much greater movement far below the surface, National Aeronautics and Space Administration scientists said yesterday. The movement was measured at a site about 31 miles south of the quake's epicenter about a week after the Oct. 17 quake, the said. The measurement relied on the random electronic signals that are routinely emitted by stars billions of light-years from earth.

1990's: IAA joins the world

We were very pleased to be visited by Andrej Finkelstein, Sergei Pograbenko & Irina Kumkova in 1989, telling us about IAA and the plans for the QUASAR project.

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IAA visits Washington

Visiting President Bush (the first one)

This is Nice (in France)

40

The 1990's – The Mark-4 Era

- More Data Bandwidth
  - ⇒ Higher Sensitivity
- More Spanned Bandwidth
  - ⇒ More Precision on Delay Measurements
- Smarter Schedules
  - ⇒ Better Data Accuracy
- New, High Quality Stations & Better Networks
- Expanded Correlator Capacity

ALL OF WHICH MADE BIG IMPROVEMENTS IN DATA QUALITY

41

The 1990's – The Mark-4 Era

BUT – These data improvements came at the cost of many, many problems with:

- High Density Tape Recorders
- Recording Heads
- Expensive Tape
- Expensive Tape Reels
- Tape Shipping Problems
- Etcetera!

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Mark-5: The New Millenium

- Tape & Tape Recorders have **always** been a major weakness of VLBI:
  - Heads are expensive - Tape is expensive to buy
  - Mechanical problems in recorders - Tape shipping problems
  - Reliability at stations is poor - Etcetera
- The cost of large consumer disk drives falls below the cost of tape. Each disk drive contains the mechanical drive & heads in ~2000.
- Mark-5: VLBI uses an array of computer disks & **NO TAPE !! NO HEADS !! NO RECORDERS !!**

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Real Mark-5A Hardware

8 standard disk drives fit in two trays for each terminal. Each disk drive is typically ***2+Terabits*** (> 250+ Gbytes)

E-VLBI in the New Millenium

- In addition, all the Mark-5 hardware is now able to send data bits through the Internet.
- When big Internet "pipes" are available at all stations (a few hundred Mbits/sec), then VLBI can run in *real-time* without the need to ship any data (No UPS or FedEx !).
- When the "pipes" are smaller, then data can be sent back more slowly (like one day to send 2 hours) after using Mark-5 disk as a buffer. This may be faster & cheaper than sending via UPS/FedEx.
- EVLBI can use "dark fibres" that are spares.

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VLBI – My 35 Exciting Years ! !

- For me, the past 35 years have been a very exciting challenge.
- A group of colleagues built from zero a scientific measuring "engine" that improved measurement accuracy by many orders of magnitude.
- We transferred the technology to many new partners around the world.
- We made many new friends and became global travellers.
- Our work has been appreciated by our scientific colleagues.

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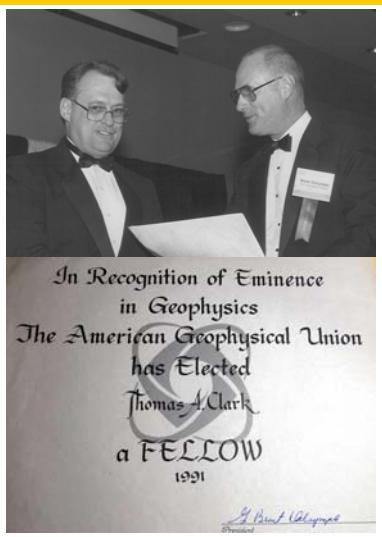
AGU Honors the VLBI Group

- Bowie Medal:
  - Irwin Shapiro
- Macelwane Medal:
  - Tom Herring
- AGU Fellows:
  - Chuck Counselman
  - Alan Rogers
  - Tom Herring
  - Tom Clark



An Honor from Goddard:

And now the IAA Medal !

Tom Clark

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A few photos - Svetloe

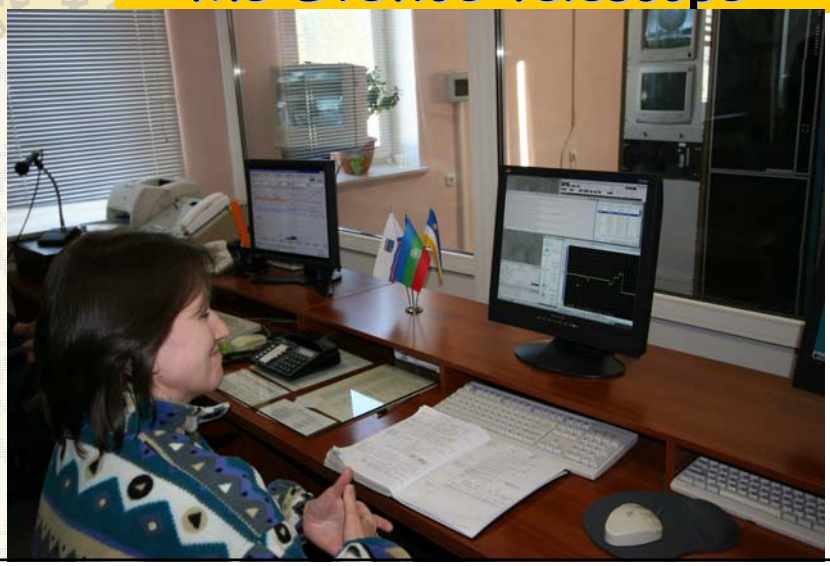
Sasha Ipatov and me at Svetloe

51

Svetloe's Control Room

52

Mark-4 Field System running the Svetloe telescope



The Frozen Baltic Sea

The Frozen Baltic Sea

The Frozen Baltic Sea

Coffee in Andrei's Office

57

Parties every night

Touring the IAA Labs

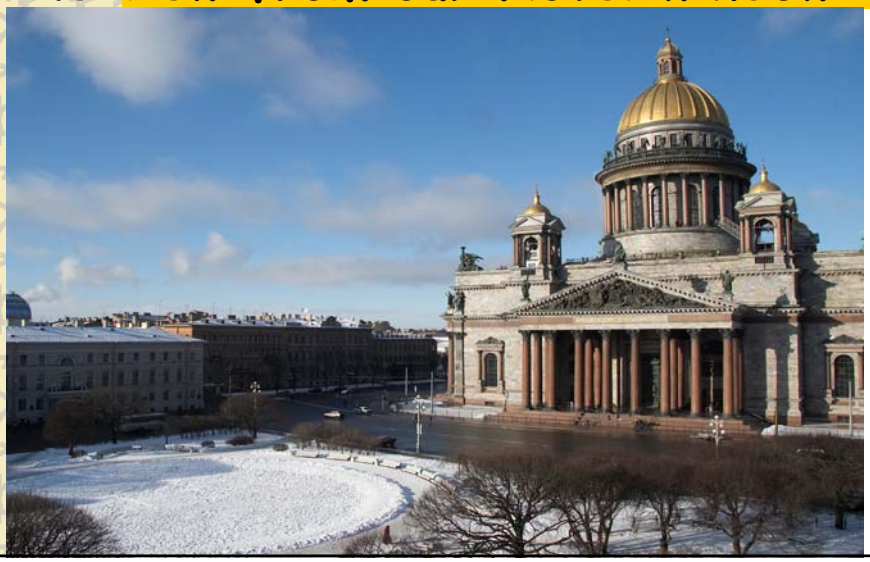
With every meeting --Vodka!

And with Jack !

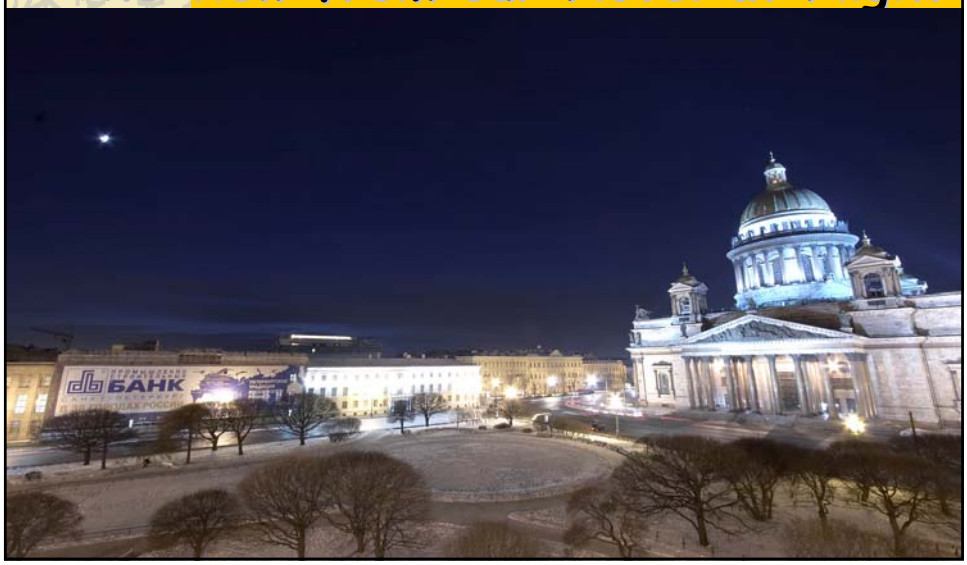
61

The Hermitage

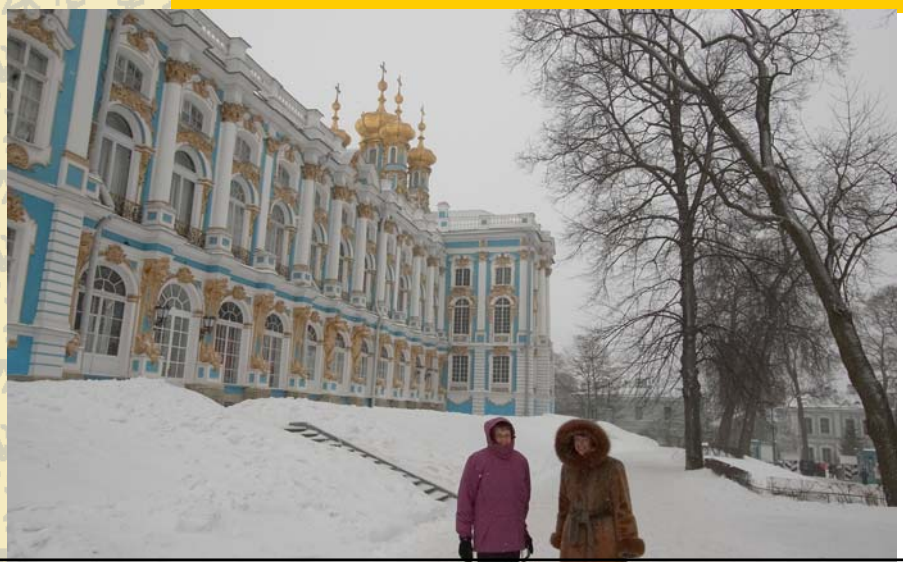
St. Isaak's Cathedral
The view from our Hotel window



St. Isaak's Cathedral
The view from our Hotel at Night



Cathrine's Palace @ Pushkin in the snow



Dinner at Andrei's

Andrei presents the Gold Medal

Presenting the Award Lecture

Andrei, Irina, Elizabeth and Roses