NAVEX - A SPACE SHUTTLE EXPERIMENT WITH ATOMIC CLOCKS

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ABSTRACT

NAVEX is a navigation- and time transfer experiment. It will be flown within the payload of the first German Spacelab mission D-1, scheduled in June 1985. The objectives of the experiment are to synchronize distant ground stations with an accuracy of better than 10 nsec and to demonstrate one way ranging with an accuracy of better than 30 m. Spread spectrum signals will be used and the related technique will be tested. On board a Cs and a Rb clock will be used. The relativistic effect of these clocks will be about -25 μsec per day. On the ground at least two receiving stations and one transmitting-receiving station will be installed. The synchronization of the ground clocks by Shuttle signals will be compared to those achieved with clock transportations and with GPS measurements. The paper gives a system description of this experiment, containing details on the technical concept, the hardware and the planned data evaluation. The present state of the preparatory work is briefly reviewed.

INTRODUCTION

The recent successful mission of the Space Shuttle Columbia was not only a considerable success for NASA; it was also a step forward for all those experimenters who make preparations for future investigations with the Shuttle.

Such preparations are also running in Europe on the basis of an agreement from 1973 between the United States and nine European countries who contribute to the European Space Agency (ESA). This agreement provides cooperation in the development and utilization of the new Space Transportation System (STS).

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*) DFVLR = Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt, Oberpfaffenhofen
**) SEL = Standard Elektrik Lorenz, Stuttgart
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The European contribution to the development of the STS comprises the development of a SPACELAB which houses astronautes and equipment in a terrestrial atmosphere, and the development of pallets and special structures which carry experiment equipment outside of the lab in the cargo bay of the Shuttle.

A special arrangement of SPACELAB and a unique support structure (USS) with some experimental equipment is shown in Fig. 1.
This arrangement will be used on Shuttle Mission STS 26 which we call D-1-Mission, because it is the first flight booked by the Federal Republic of Germany. The SPACELAB and the pallet structure will have been space proved in earlier flights STS 9 and STS 19.

The pallet structure shown in Fig. 1 is also known under the name SPAS (Shuttle PAllet Satellite) and will be flown for the first time in spring 1983. During the D-1 Mission it will carry equipment for experiments NAVEX and MEA. MEA is a Material Experiment Assembly from the United States. NAVEX is an experiment of the Federal Republic of Germany with the aim to investigate future possible applications of space borne atomic clocks. It will be the first European step in this direction. Therefore the experiment will be confined to a few basic questions in this field: the investigation of a microwave link for comparison of on-board and ground based clocks and some test measurements for one way positioning. In both cases spread spectrum techniques with pseudo noise codes will be applied. In the following some more information on this experiment is given.

GENERAL VIEW

The Shuttle experiment NAVEX is part of the German SPACELAB utilization program. It arose from two proposals made by SEL and by DFVLR. The first concerned one-way ranging, the second time transfer with space borne clocks. During the succeeding study phase, both proposals were combined in a single experiment with the focal point on navigation; because of that the name NAVEX (= NAVigation EXperiment) was chosen.

Table I shows the main stages of the experiment evolution from proposals to the Shuttle Mission 1985. From 1977 until 1979 an engineering model was built and preliminary field measurements were performed.

Fig. 2 shows the configuration of field measurements. A Cs-clock on an airplane was compared with another on the ground by a two way microwave link. Additional range information for data analysis were received from simultaneous ranging with radar. The results were encouraging. A precision of σ_t < 10 nsec could be demonstrated (Fig. 3).
Afterwards a time lag occurred because of funding problems and by the lack of a flight opportunity. In mid 1981 the decision was made for NAVEX participation in the D-1 mission. For that some conceptual and technical modifications and reductions had to be accepted.

The modified concept and the main objectives of the experiment are shown in Fig. 4. The two way clock comparison will be accomplished by L-Band signals. Simultaneous ranging with a C-band radar will allow the determination of the propagation effects of ionosphere and the true range between Shuttle and the ground control station. By additional receiving of the L-Band Shuttle signals at two ground receiving stations the Shuttle positions during the short visible arc can be determined. For this purpose the ground stations have to be equipped with atomic clocks, which must be synchronized by additional means. After the Shuttle positions and the true ranges to the different ground stations are known with an accuracy of $\sigma_r < 10$ m, the one way positioning of a ground receiving station can be tested.

In Fig. 5 the experiment configuration is shown with the main functions of the participating installations. For the coordination of several ground stations, a central operation control is provided. The station operation control requires orbit and attitude predictions of the Shuttle from the Payload Operation Control Center (POCC) at Houston. These data will be received via the German Payload Operation Center (GPOC). NAVEX housekeeping data transfer will occur via TDRSS. During ground station contacts the on-board measurement data will be transmitted to the ground by digital modulation of the L-Band carrier.

The synchronization of the ground station clocks will be done by clock transportation and by an additional microwave link. Concerning the latter, time transfer investigations with GPS and with a communication satellite are presently going on.

At the launch site the on-board clocks will have to be checked before and after the mission. For an accurate determination of the clock frequency difference on-board and on the ground, a frequency transfer from the launch site to the control station will be necessary. We think that GPS could be a good solution for this task. Finally, after all data and time transfer, the measurement results will have to be gathered, preprocessed and recorded for the off line data evaluation.
After this rough survey some details may be outlined.

EXPERIMENT EQUIPMENT

The NAVEX specific hardware consists of the on-board station, of one ground control station and two receiving stations; it has to be completed by an AN/MPS-36 radar and by additional equipment for tests, for data handling and for ground clock synchronization and frequency transfer.

The on-board equipment is mounted on three GAS-containers. (GAS = get away specials). These containers were chosen because they will be available and already space proved from another experimental program. These three containers and three antennas are mounted on a SPAS structure (Fig. 6). The accomodation in the cargo bay of the Shuttle is shown in Fig. 7. The geometry is such that cable lengths between containers and the Spacelab subsystems are minimized, that good antenna viewing angles are achieved and that optimal environmental conditions are obtained. Fig. 8 shows the functional assemblies of the on-board station and the main signal flow with the RF- and Base Band (BB) signal interfaces: Container # 1 contains the onboard time reference assembly (OTR) with a Cs- and a Rb-frequency standard, a phase comparator, a divider and synthesizer, clock interface, power supply, redundancy switch and a battery. Container # 2 includes the receiver assembly, the measurement assembly with code modulator and demodulator and a time interval measurement unit, a processor assembly with the data acquisition control system (DACS 11-N), with a memory module and with I/O-modules for operation control, and a second power supply. Finally container # 3 contains the L-band transmitter with PSK-modulator, preamplifier and a 25 W RF-power amplifier, the C-band radar transponder and a third power supply.

Fig. 9 shows the ground control station, which contains very similar functional assemblies as the onboard station without the radar transponder. The receiver station (Fig. 10) is identical to the control station without the transmitting equipment.

The main technical parameters concerning the RF-links between Shuttle and ground stations are given in Table II.

As for the additional equipment, only that for synchronization of the ground stations and for frequency transfer should be mentioned here. The basis for synchronization will be clock transportations. In cooperation with our national time institute 'Physikalisch-Technische Bundesanstalt' (PTB) several clock transportations over a distance of 700 km between PTB and DFVLR have been carried out with an accuracy of $\pm$ 5 nsec. Moreover GPS-signals should be received at the different groundstations and used for synchronization according to the 'Common View Technique' [12]. For preliminary investigations of this opportunity an experimental GPS receiver was built and C/A code signals from several satellites were received. Fig. 11 shows the fluctuation of single point measurements. The difference between the NAVEX-master clock and GPS time was taken every two seconds. The RMS of these single samples was σ = 54 nsec. By averaging on 300 samples, received during 10 minutes observation time, the RMS could be reduced to σ = 3 nsec. With these more precise mean values a frequency comparison between GPS- and the NAVEX master clock could be made during more than 10 days. The results received with NAVSTAR SV # 6 are shown in Fig. 12. As the frequency difference between USNO-masterclock and GPS time is known from USNO-Time Service for the same period, the frequency difference between USNO-MC and NAVEX-MC could be calculated. The results let us anticipate that slowly varying systematic errors will be small enough for a frequency transfer with sufficient accuracy. These measurements will have to be continued.

EXPERIMENT OPERATIONS

The D-1 mission will have a duration of 7 days. The operating time of the

NAVEX onboard equipment will be about 150 hours. An overall timeline of the onboard operations is given in Fig. 13.

The equipment of container # 1, these are mainly the clocks, will be running all the time. The equipment of containers # 2 und # 3 will be switched on only when passing the ground stations because of power constraints. Every day 6 successive passes will occur during a time span of 8 hours.

The timeline during each pass is shown in Fig. 14. The activation of transmitters will occur before the Shuttle appears at the horizon of the ground stations. The duration of each contact to the ground stations will be 5 to 8 minutes. After that the transmitters and other equipment of containers # 2 and # 3 will be switched off again. The changing power consumption of the NAVEX onboard equipment is shown in Fig. 15.

The data links between the Shuttle and the ground stations and the ground data net are shown in Fig. 16. Besides a data and voice link via TDRSS and POCC to the GPOC, a direct data transfer of 250 bit/sec is provided from the Shuttle to the NAVEX ground stations. Between the ground stations and the NAVEX operation control center, the data transfer will be executed by a 1.2 k bit/sec data link, by telex, by telephone and by magnetic tapes. The data exchange between GPOC and NAVEX operation control needs no special equipment, because both will be housed in the German Satellite Operation Center (GSOC) at DFVLR Oberpfaffenhofen and because the same data system will be used by both.

DATA EVALUATION

The raw data coming from the Shuttle via POCC, from the ground stations and from auxiliary measurement devices, as for instance refractometers, have to be preprocessed for two different purposes (Fig. 17): one is the near real time evaluation, necessary for antenna pointing, Doppler frequency predictions and for data monitoring; the other is the production of an experiment tape for the off-line data evaluation. The main points of the off-line evaluation are given by the experiment objectives in Fig. 4.

The principle of two way clock comparison between on-board and ground based clocks is illustrated by Fig. 18. The time difference ΔT between both can be calculated from time interval measurements onboard and on the ground. Transmitter and receiver delays have to be determined before the mission and will be controlled before and after each pass. The upward and downward propagation delays will be somewhat different because of the relative motion between Shuttle and ground station and because of the different ionospheric influence on the two signal frequencies. Taking this into consideration, ΔT can be determined by the formula

(1) $$\Delta T = T_G - \frac{1}{2} T_S + \frac{1}{2} \left[(\tau_{TG} - \tau_{TS}) + (\tau_{RS} - \tau_{RG}) + (\tau_{L2} - \tau_{L1}) \right]$$

T_G = time difference measured at ground station

T_S = time difference measured onboard

τ_{TG} = delay time of ground transmitter

τ_{TS} = delay time of onboard transmitter

τ_{RG} = delay time of ground receiver

τ_{RS} = delay time of onboard receiver

τ_{L1} = delay time of downward signal

τ_{L2} = delay time of upward signal

Because of the relativistic effect a frequency deviation of the onboard clocks relative to the ground master clock is expected. This causes an increasing time difference Δt between both clocks according to the formula

(2) $$\Delta t = \frac{1}{c^2} \int_0^t [\frac{1}{2} (v_s^2 - v_{gr}^2) - (\phi_s - \phi_{gr})] d\tau$$

v_s = Shuttle velocity

v_{gr} = velocity of ground station

ϕ_2 = gravity potential at the Shuttle

ϕ_{gr} = gravity potential at the ground

c = velocity of light

Fig. 19 illustrates the increase of the expected time difference during one revolution of the Shuttle for orbit eccentricities e = 0 and e = 0,01.

For the determination of the ionospheric propagation effect, the range rate dr/dt between control station and Shuttle has to be taken into account in a similar way as for the two way time transfer

(3) $$\Delta r = \int_{\tau_{TS}}^{T_s - \tau_{RS}} \frac{dr}{dt}(t)\, d\tau \approx c \cdot \Delta\tau_{L\,2}$$

c = velocity of light.

The frequency dependence of the ionospheric refractive index N_I can be described in the frequency range from 1 to 6 GHz by the relationship

(4) $$N_I = -\frac{40{,}3 \cdot 10^6\, N_e}{f^2}$$

$N_I = (n_I - 1) \cdot 10^6$ = modified refractive index of ionosphere
N_e = electron density in electrons/m^3
f = signal frequency in Hz

as was verified by [10].

From this the integral ionospheric effect $\Delta\tau_I$ can be calculated by integration of N_I along the ray path between Shuttle and ground control station

(5) $$\Delta\tau_I\,(f) = \frac{10^{-6}}{c} \int_{s_c\,(\text{Control Station})}^{s\,(\text{Shuttle})} N_I\,(s)\, ds \approx \frac{40{,}3}{c \cdot f^2} \int_{s_c\,(\text{Control Station})}^{s\,(\text{Shuttle})} N_e\,(s)\, ds.$$

The integral on the electron density on the right side of the above equation is called electron content along the ray path. Its value can be determined by delay time measurements at different frequencies. For the special case of NAVEX this electron content can be determined from corrected delaytime measurements in L-band $(\tau_{L1} + \tau_{L2})$ and in C-band $(\tau_{C1} + \tau_{C2})$ using the formula

(6) $$(\tau_{L1} + \tau_{L2}) - (\tau_{C1} + \tau_{C2}) = (\Delta\tau_{IL1} + \Delta\tau_{IL2}) - (\tau_{C1} + \tau_{C2})$$

$$\approx \frac{-40{,}3}{c} \int_{s_c\,(\text{Control Station})}^{s\,(\text{Shuttle})} N_e\,(s)\, ds \cdot \left[\frac{1}{f_{L1}^2} + \frac{1}{f_{L2}^2} - \frac{1}{f_{C1}^2} - \frac{1}{f_{C2}^2}\right].$$

$\Delta\tau_{IL1}$, $\Delta\tau_{IL2}$ = ionospheric delays in the L-band

$\Delta\tau_{IC1}$, $\Delta\tau_{IC2}$ = ionospheric delays in the C-band

The influence of the troposphere is assumed to be independent of frequency. It can be determined by integration on the known profile of tropospheric refractive index N_{TR}

(7) $$\Delta\tau_{TR} = \frac{10^{-6}}{c} \int_{s\ (\text{Troposphere})} N_{TR}(s)\, ds ,$$

when the height of the ground station and the refractive index at the ground station are known.

For accurate Shuttle position determination, corrections have to be derived from control station measurements for the receiving station one-way measurements. For this purpose a simple ionospheric model may be sufficient for estimating the electron content along the ray path from the Shuttle to the receiving stations [9].

(8) $$\int_{s_c\ (\text{Control Station})}^{s\ (\text{Shuttle})} N_e(s)\, ds \xrightarrow[\text{model}]{\text{ionospheric}} \int_{s_R\ (\text{receiving Station})}^{s\ (\text{Shuttle})} N_e(s)\, ds$$

The determination of ground station positions relative to each other has been carried out by TRANSIT measurements in cooperation with the 'Institut für Angewandte Geodäsie' (IFAG) Frankfurt. An accuracy of Δx, Δy, $\Delta z < 1$ m has been achieved.

Finally the accuracy of one way pseudo range measurements for a ground station position determination may be evaluated by using the relation

(9) $$(x_G - x_i)^2 + (y_G - y_i)^2 + (z_G - z_i)^2 = r_i^2 = c^2 \cdot (\tau_i - \Delta T)^2$$

$i = 1, 2, 3, 4$

x_G, y_G, z_G = coordinates of ground receiving station

x_i, y_i, z_i = coordinates of the Shuttle at four different points of time

τ_i = propagation delay times after ionospheric and tropospheric corrections.

This procedure is well known from GPS and need not be explained any more. The ionospheric and tropospheric corrections will be made as mentioned before.

EXPERIMENT ORGANIZATION

The implementation of the experiment will be supported by several organizations with different activities:

DFVLR-PT/Köln:	Project D-1 and NAVEX management
SEL/Stuttgart:	Hardware development, manufacturing and receiving station operation
DFVLR-NE and WT: Oberpfaffenhofen	Operation control and data evaluation Ground control station and radar Synchronization of groundstations Frequency transfer German Payload Operation Center
PTB/Braunschweig:	Receiving station and primary clock
BMFT/Bonn:	Funding support
USNO/Washington:	Support for frequency transfer.

The main funds come from the Bundesministerium für Forschung und Technologie (BMFT) and from DFVLR.
The time schedule is shown in Fig. 20.
The main events will be the delivery of the NAVEX onboard equipment in spring 1984 and the Shuttle mission D-1 in mid-1985.
Concerning the D-1 mission a special agreement was signed by NASA and by DFVLR in September 1982, in which NASA assured the necessary support.

ACKNOWLEDGEMENT

The authors are indebted to their colleagues at DFVLR and SEL, who contributed to the results presented here. Particularly mentioned should be Mr. K. Friedel and R. Schimmel, who contributed Figures 16 and 19.

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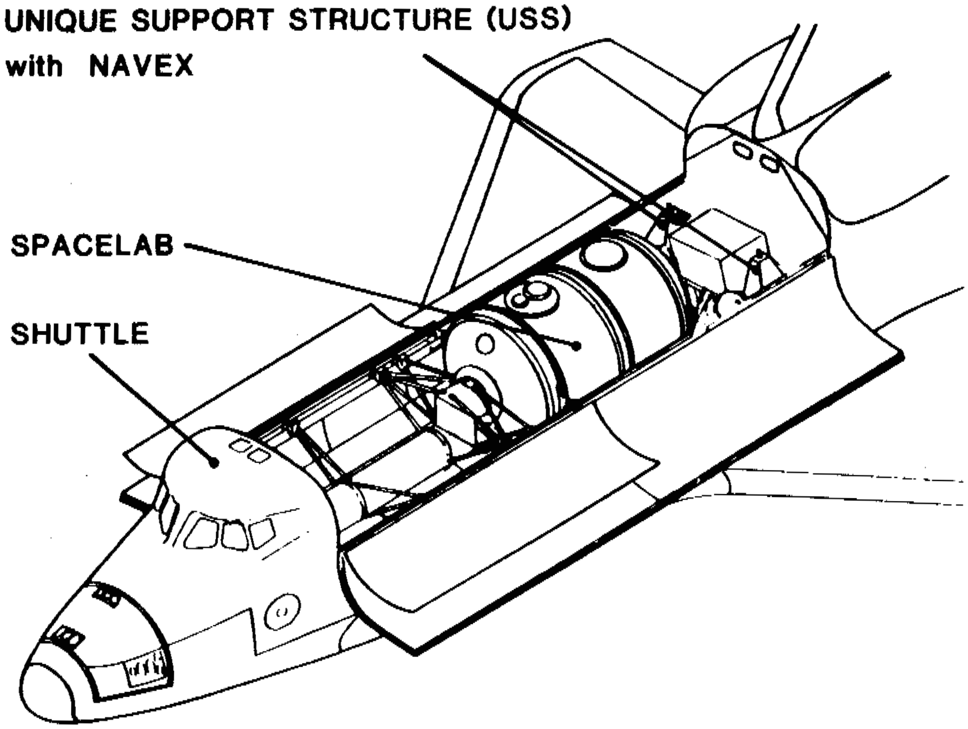


Fig. 1 - Payload of Spacelabmission D1

1974	PROPOSAL ON ONE WAY RANGING; PROPOSAL ON TIME TRANSFER
1975	SPACELAB-UTILIZATION STUDY
1976	NAVEX-FEASIBILITY STUDY
77/78	ENGINEERING MODEL DEVELOPMENT
78/79	PRELIMINARY MEASUREMENTS
80/81	SEARCH FOR A FLIGHT OPPORTUNITY
1981	DECISION FOR D-1 PARTICIPATION CONCEPT MODIFICATIONS
1982 – 1984	HARDWARE DEVELOPMENT EXPERIMENT PREPARATIONS AND TESTS
1985	SHUTTLE MISSION D-1 (STS 26)
1986	DATA EVALUATION

Table I - The NAVEX-Story

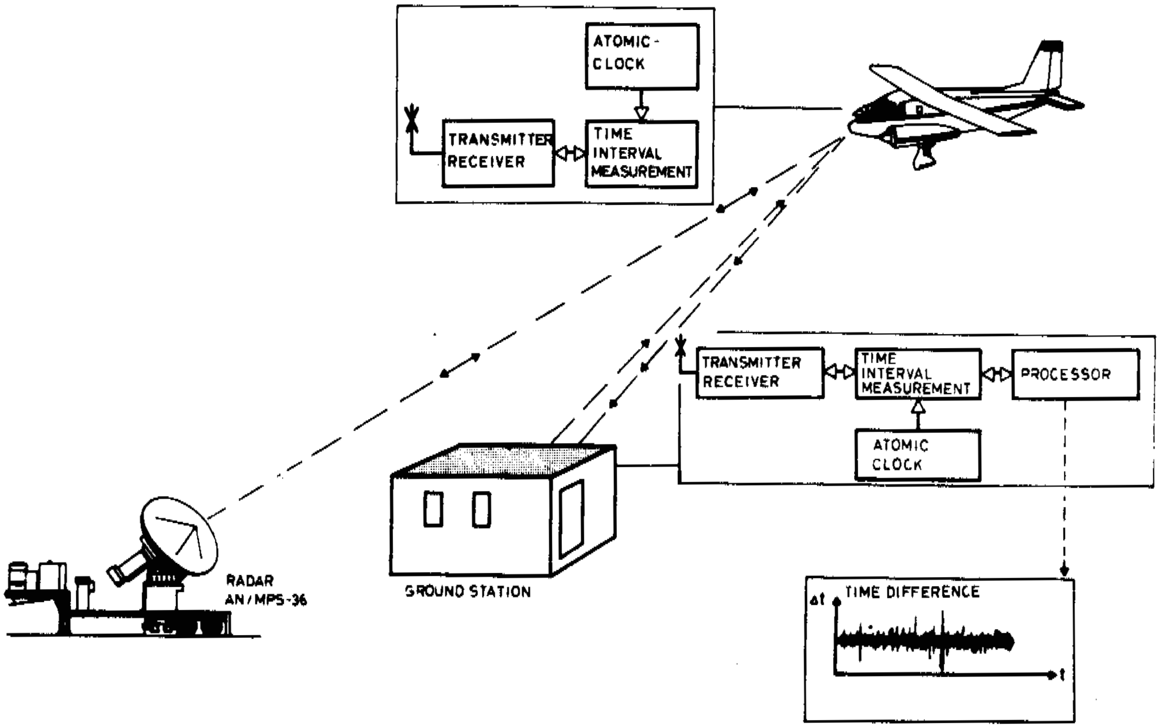


Fig. 2 - Comparison of on-board and ground based clocks by a two-way microwave link

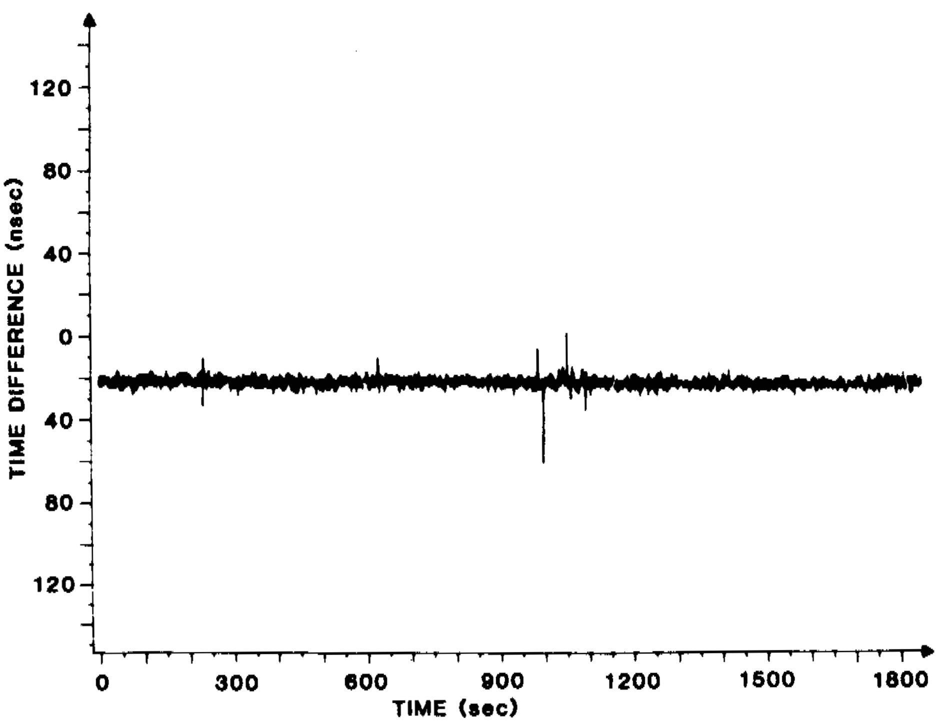


Fig. 3 - Result of a preliminary experiment with aircraft

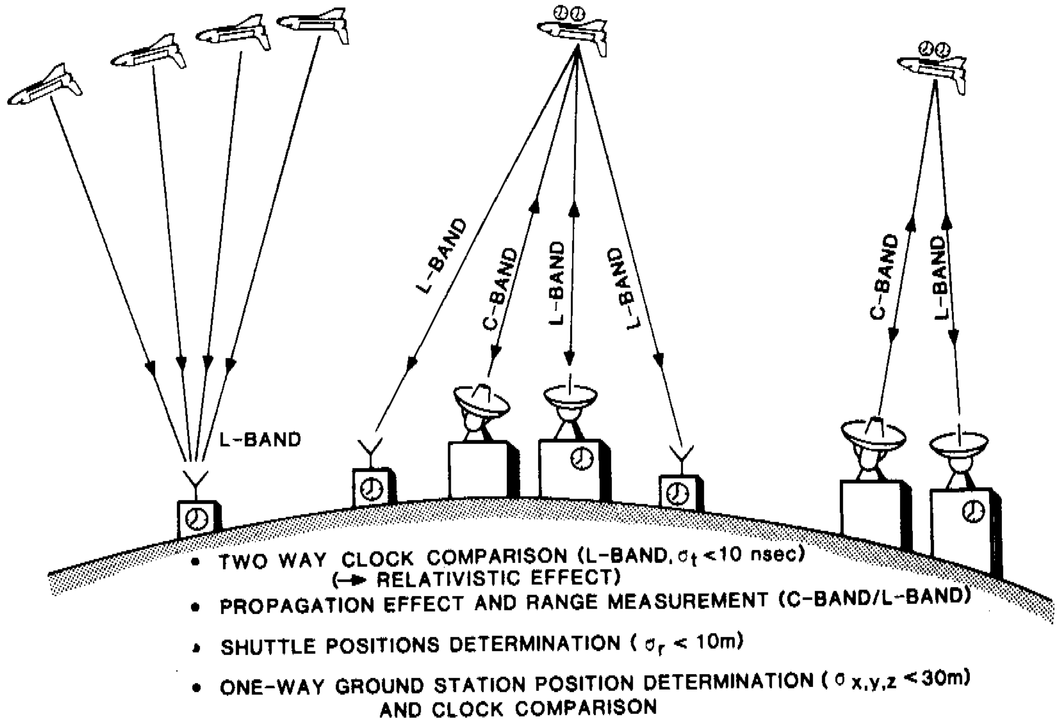


Fig. 4 - NAVEX - Objectives

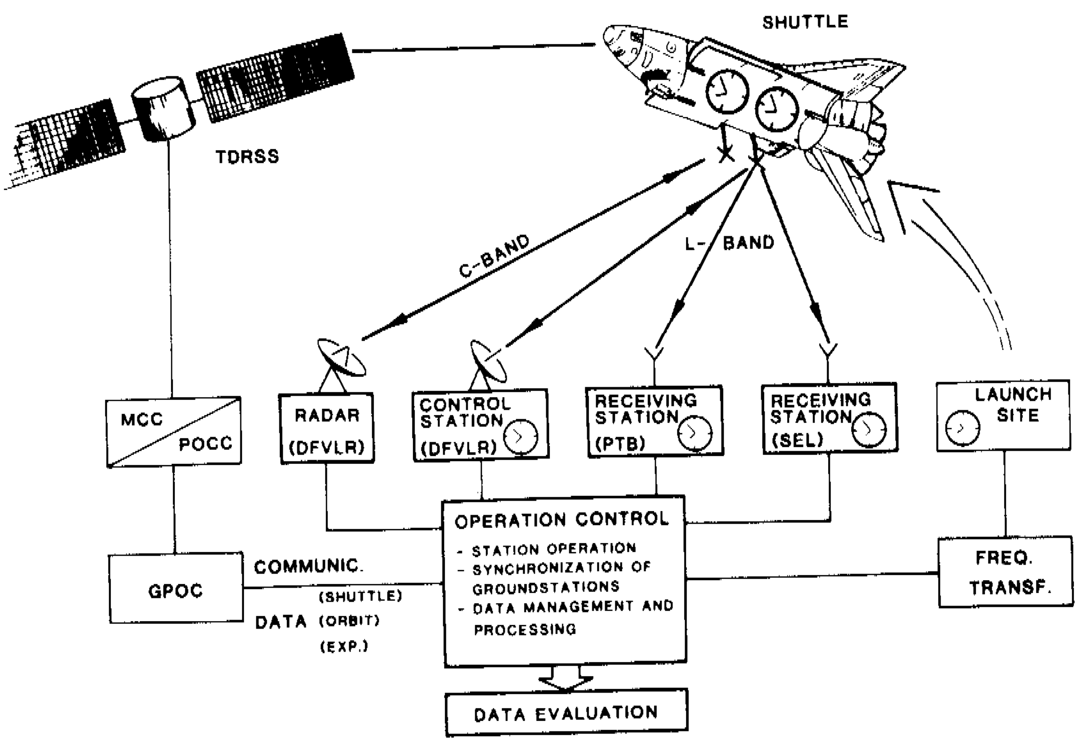


Fig. 5 - NAVEX - Experiment Configuration

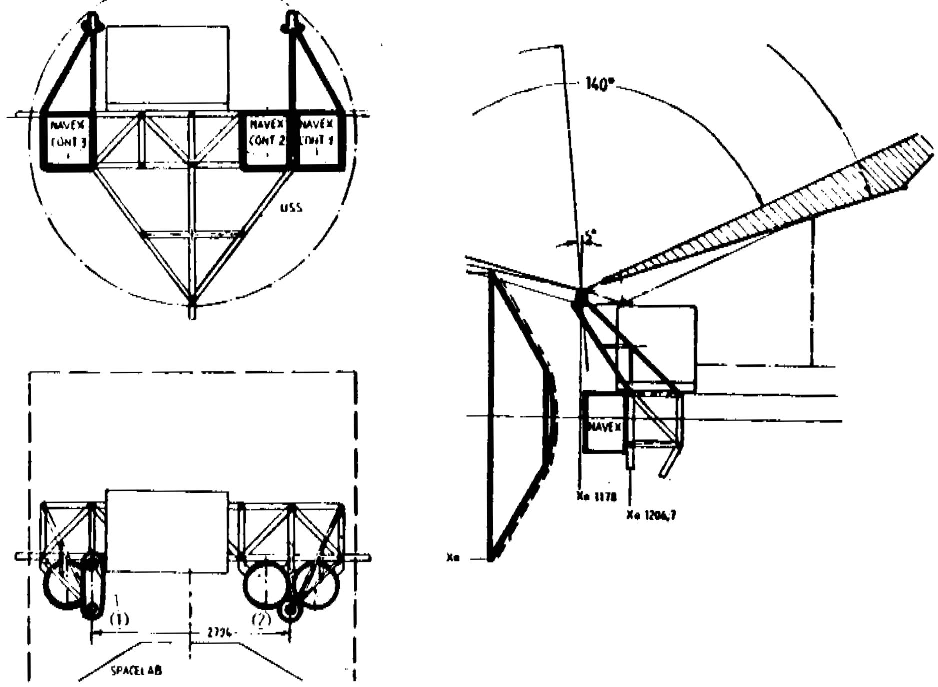


Fig. 6 - Accomodation of on-board station

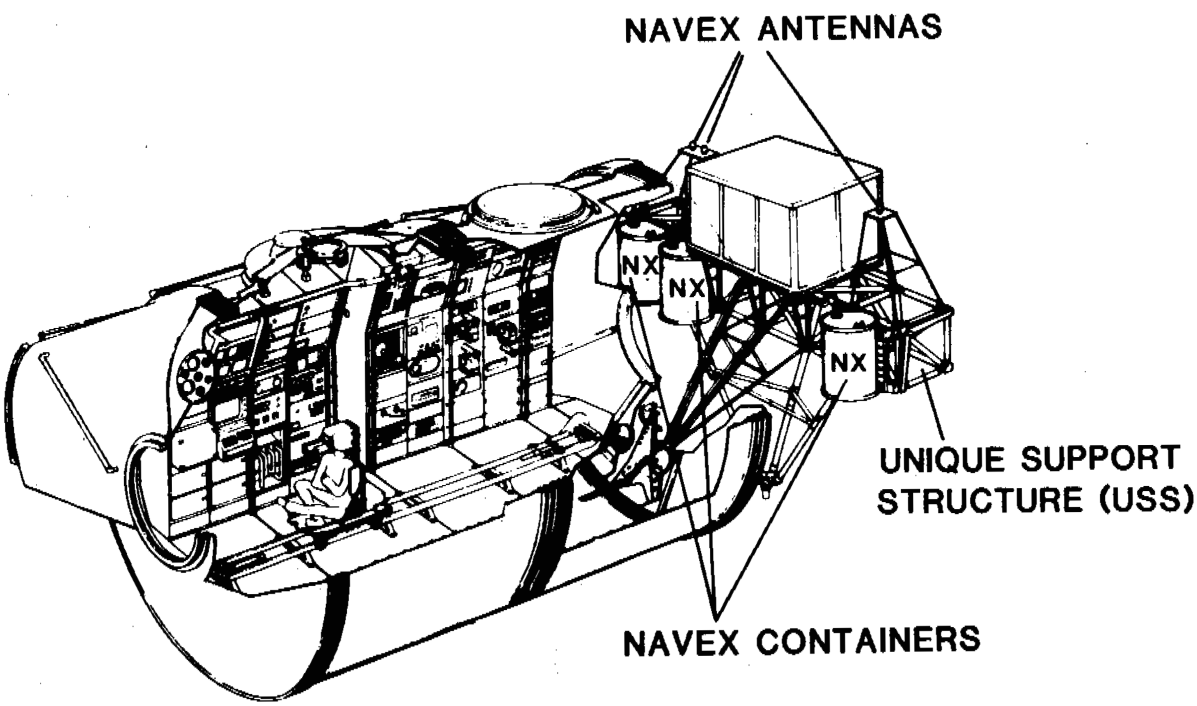


Fig. 7 - Configuration of on-board equipment

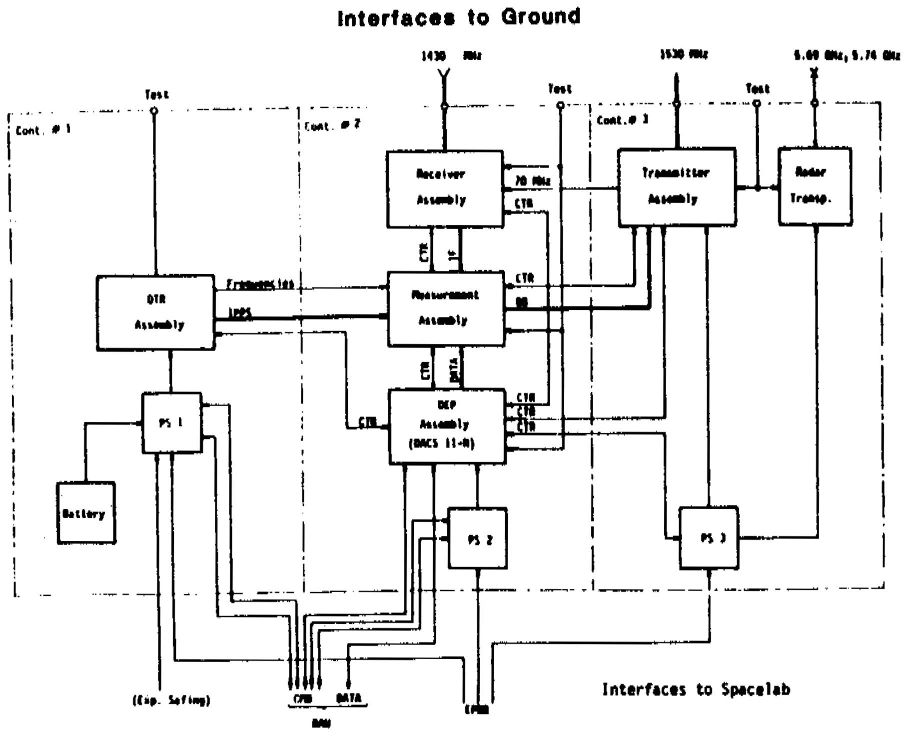


Fig. 8 - Onboard Station

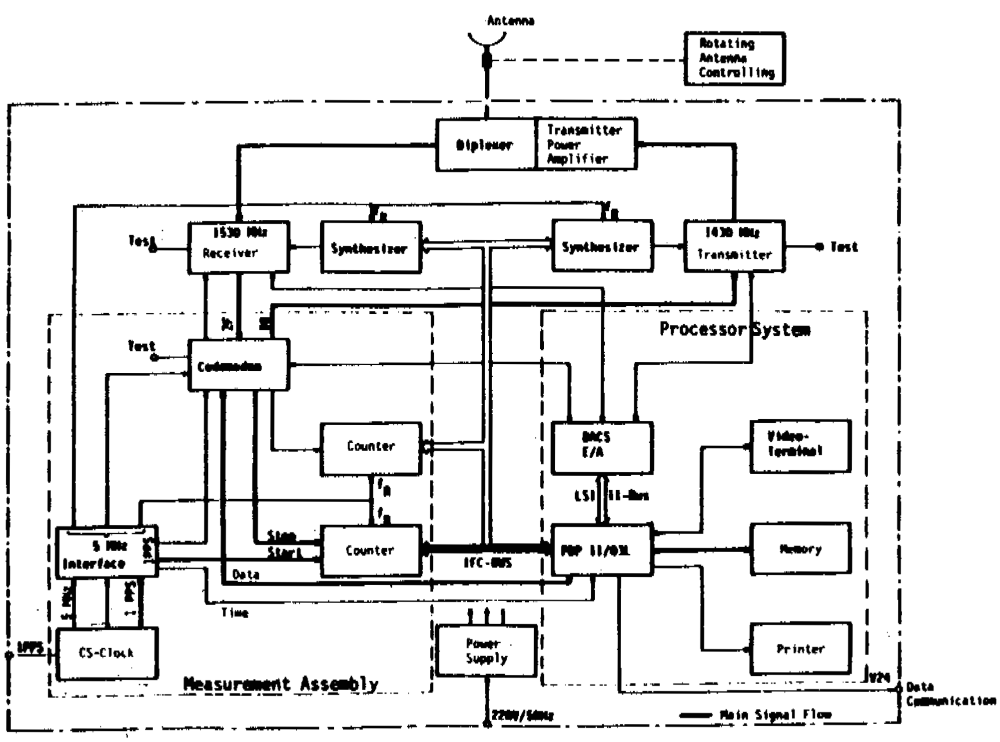


Fig. 9 - Ground Control Station

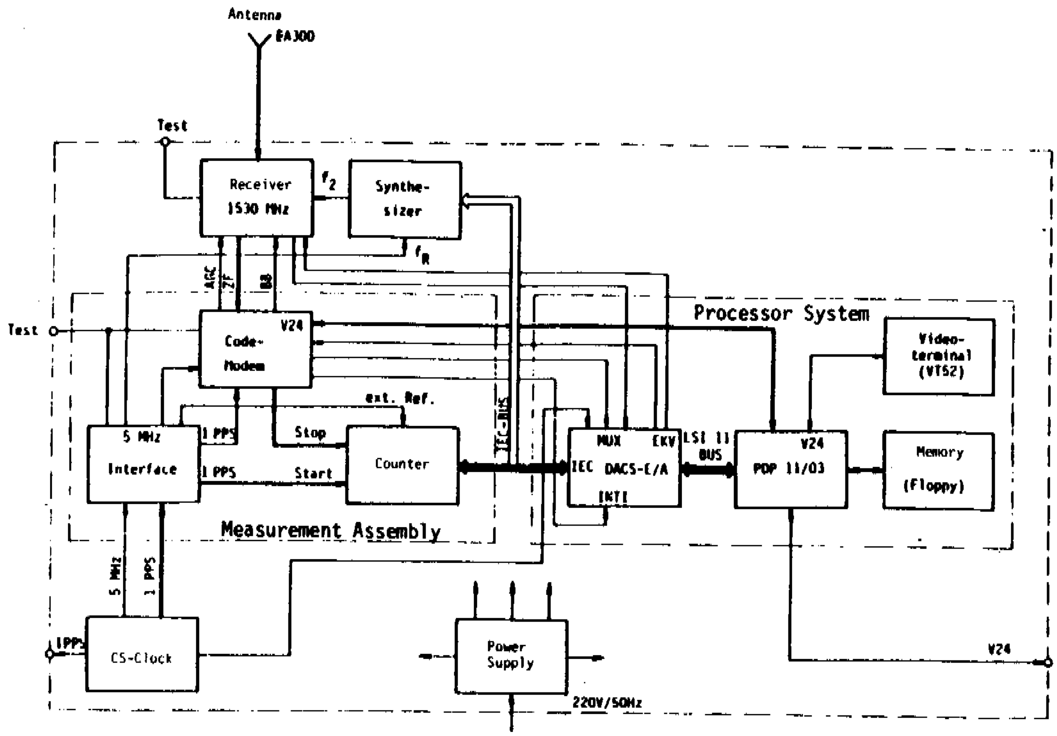


Fig. 10 - Receiver Station

Signal Parameters	Onboard Station	Ground Control Station	Receiver Station
Transmit frequency	1.53 GHz	1,43 GHz	--
Receiving frequency	1.43 GHz	1,53 GHz	1.53 GHz
RF-Power	25 W	25 W	--
Antenna gain	-1 ÷ 5 dB	24 dB	-1 ÷ 5 dB
Receiving level	-79...-99 dBm	-83...-101 dBm	-99...-125 dBm
Signal to Noise Ratio (S/N at B=2MHz)	+28...+8 dB	+24...+6 dB	+7...-19 dB
Doppler shift	--	± 37 kHz	± 37 kHz
Code Clock Frequency	1023 kHz	dto.	dto.
Number of codebits	1023	dto.	dto.
Code period	1 ms	dto.	dto.
Data Rate	250 Bit/s	dto.	dto.
Modulation	2 - PSK	dto.	dto.
Bandwidth	ca. 2 MHz	dto.	dto.
Acquisition time	15 s	15 s	20 s

Table II - NAVEX - Signal Parameters

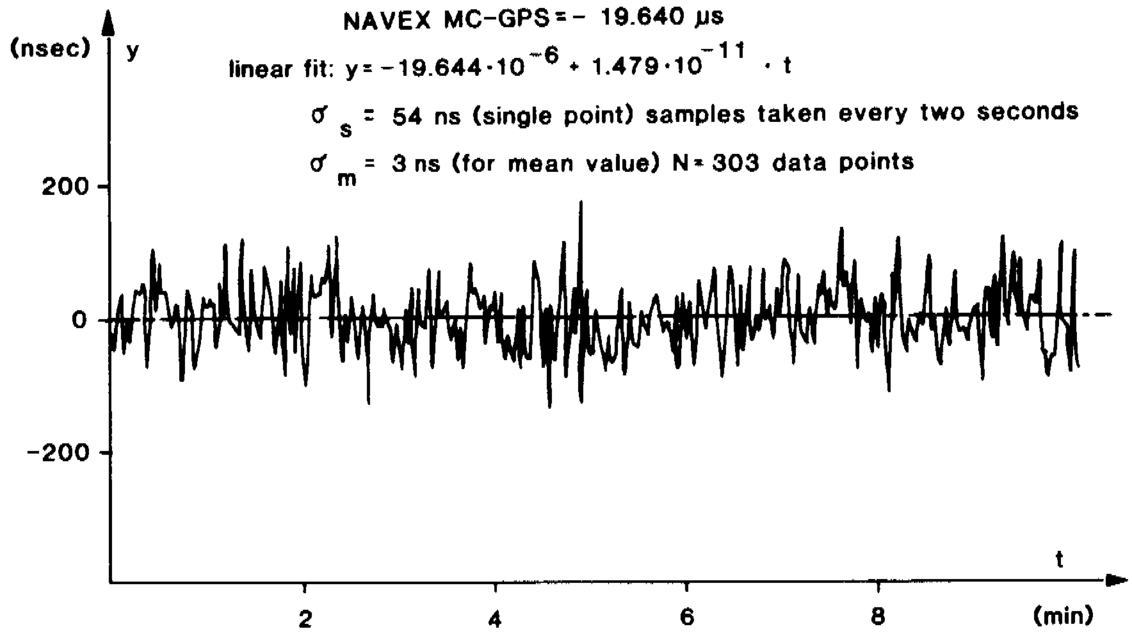


Fig. 11 - Time comparison with GPS NAVSTAR SV # 6

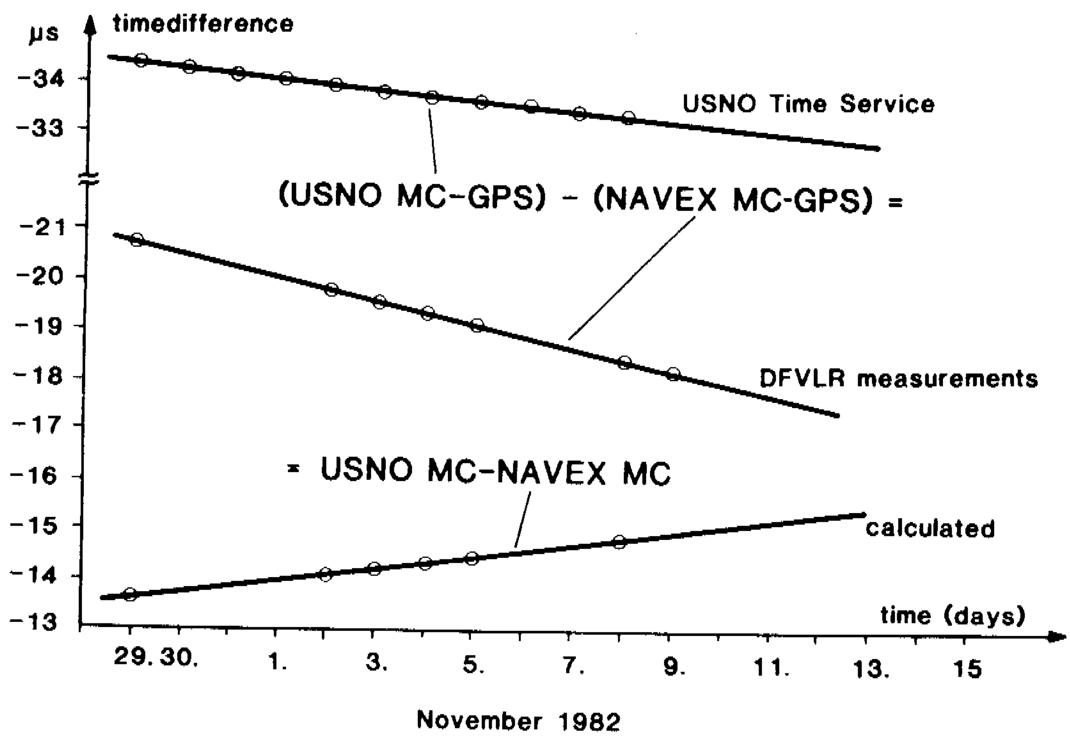


Fig. 12 - Frequency comparison between USNO MC and NAVEX MC with GPS NAVSTAR SV # 6

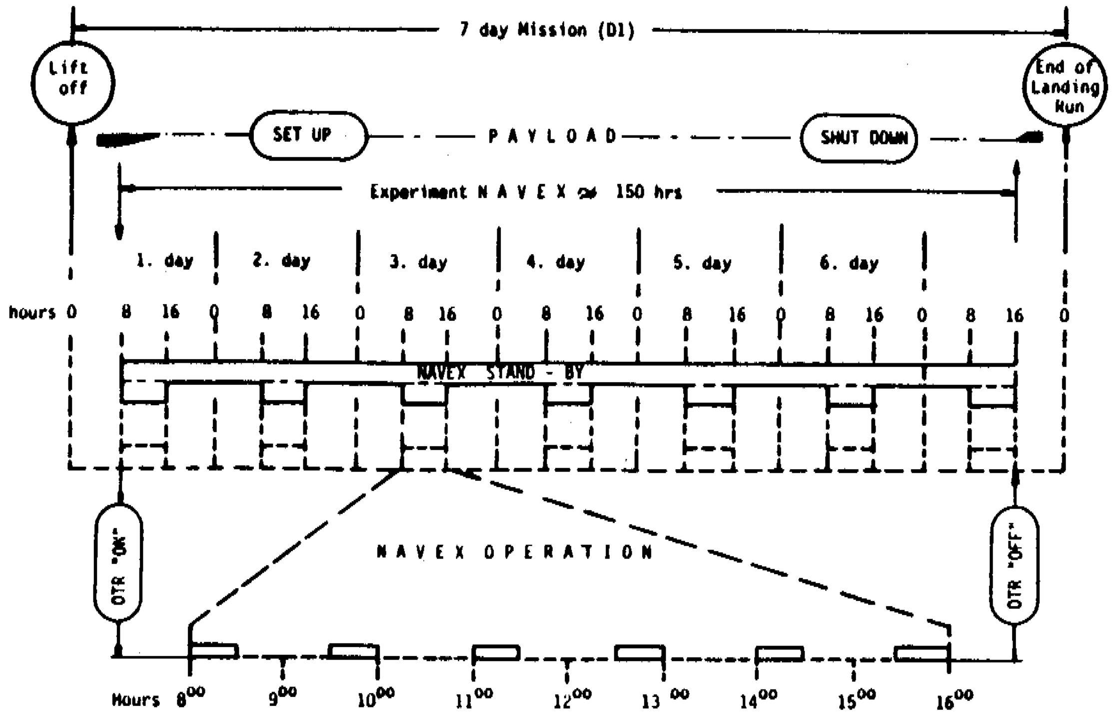


Fig. 13 - Timeline of PLE-NAVEX operations

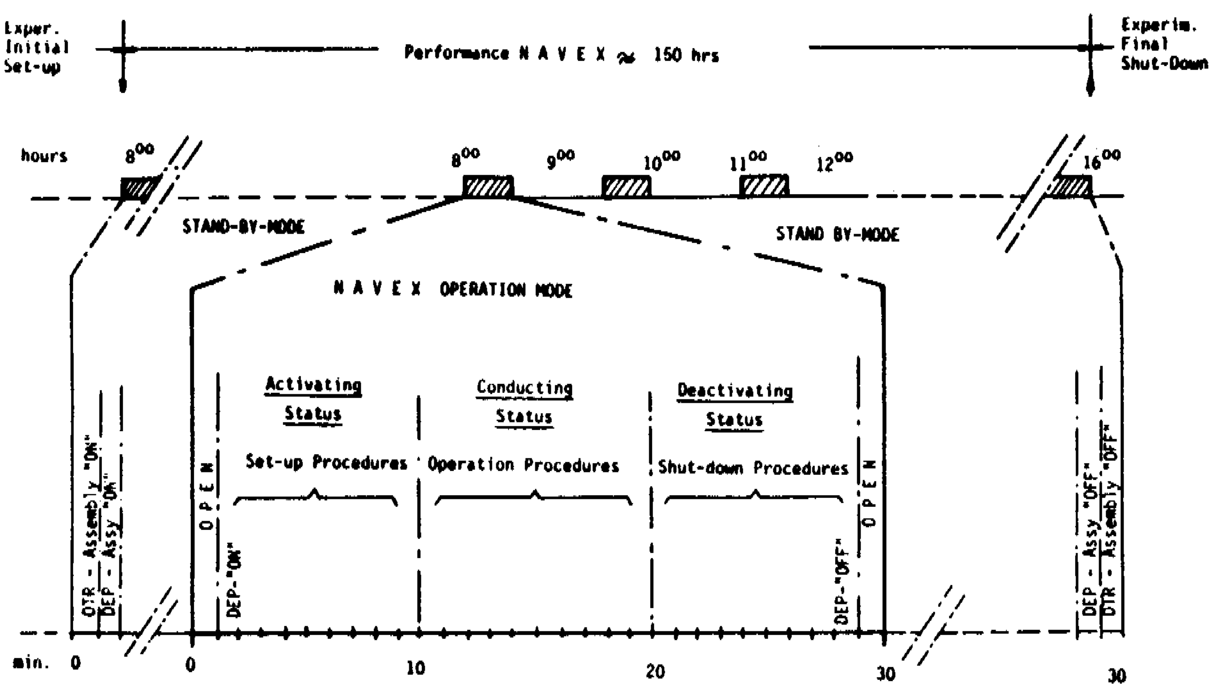


Fig. 14 - Timeline of element operation

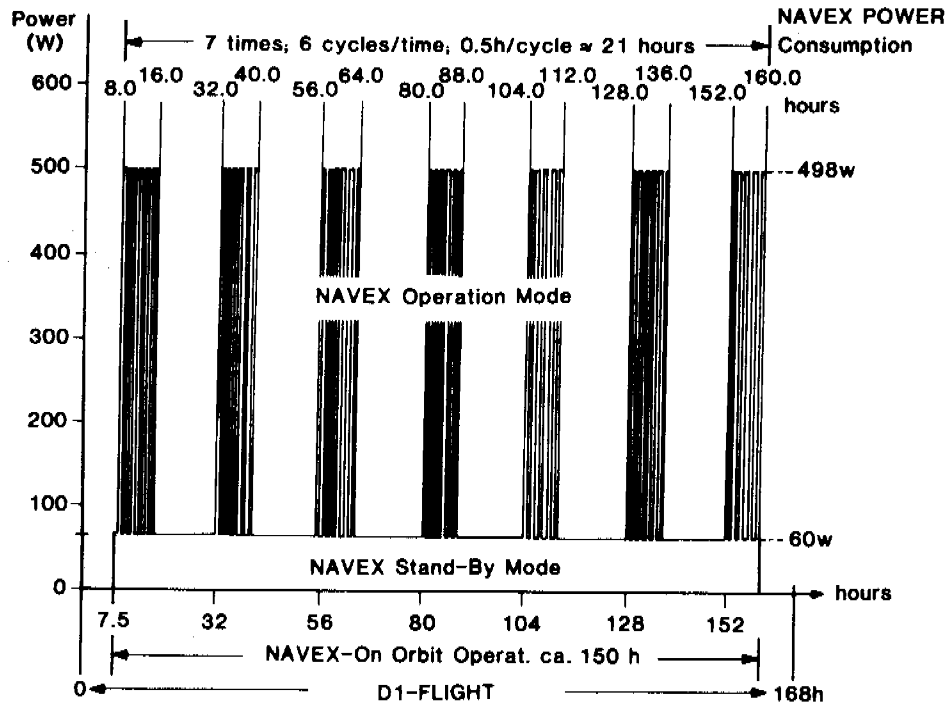


Fig. 15 - Typical power load modes

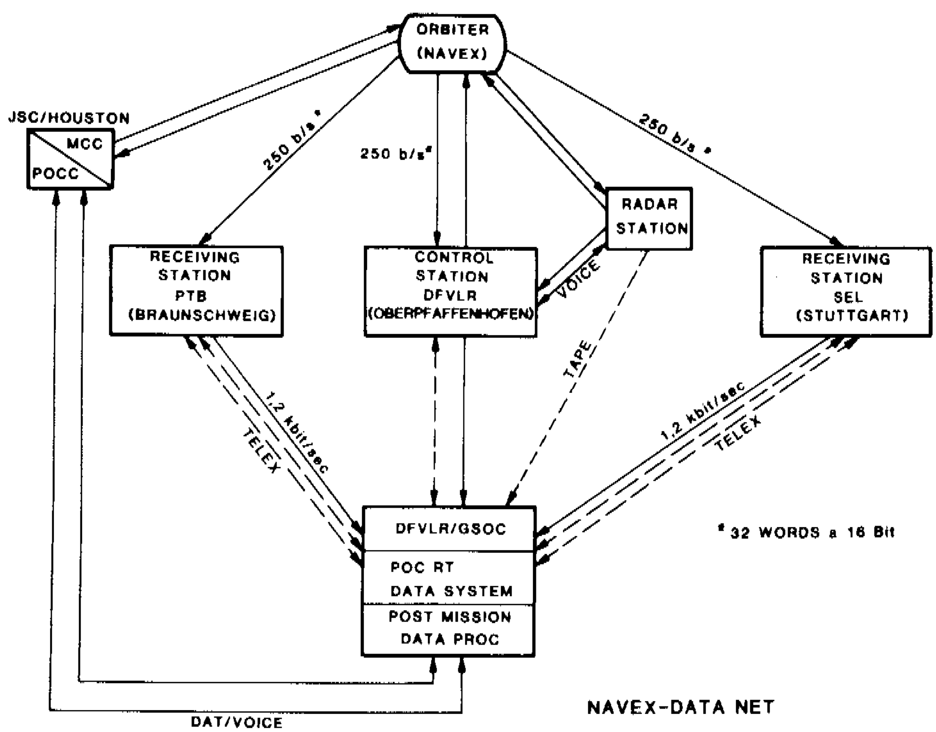


Fig. 16 - NAVEX-Data net

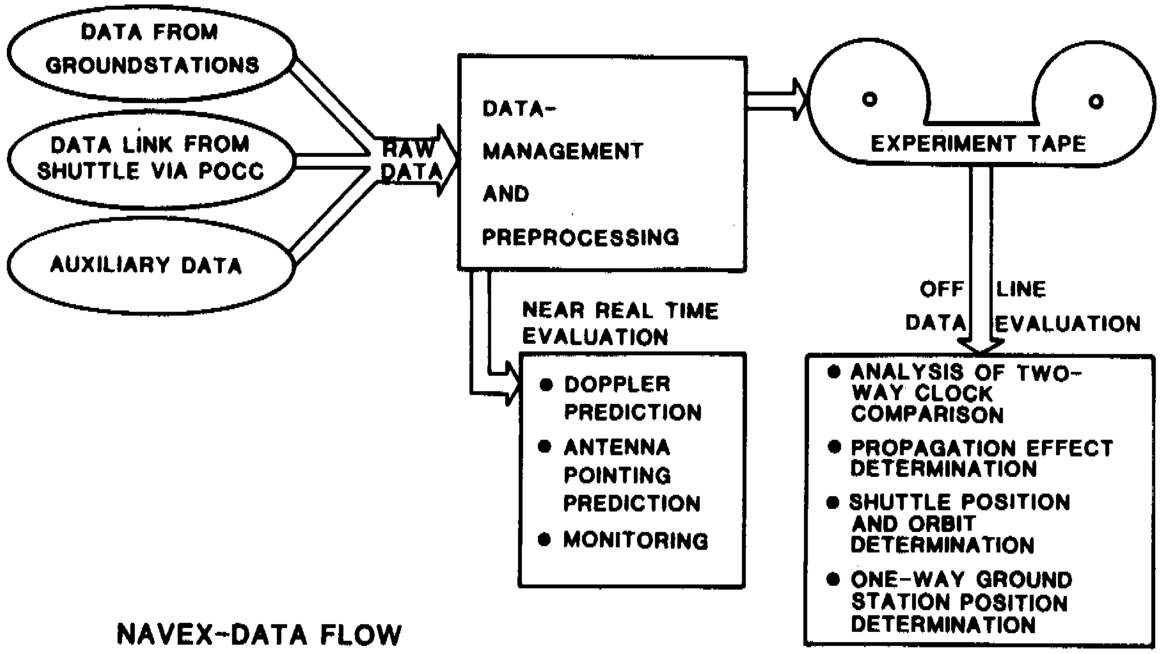
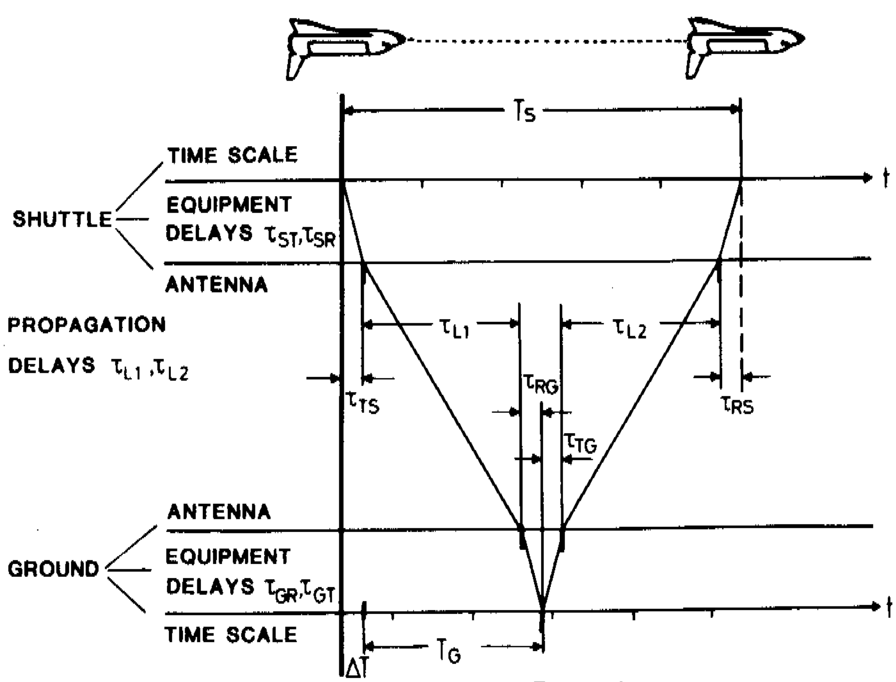
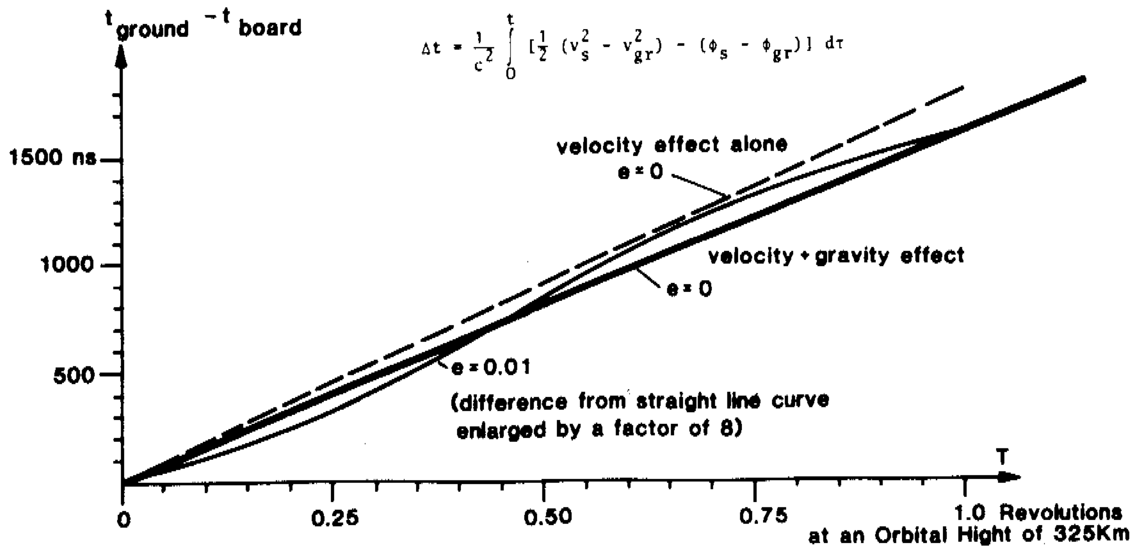


Fig. 17 - NAVEX-Data flow



$$\Delta T = t_{GROUND} - t_{SHUTTLE} = T_G - \frac{T_S}{2} + \frac{1}{2}\left[(\tau_{TG} - \tau_{TS}) + (\tau_{RS} - \tau_{RG}) + (\tau_{L2} - \tau_{L1})\right]$$

Fig. 18 - Principle of two-way clock comparison



EXPECTED RELATIVISTIC TIME DIFFERENCE BETWEEN IDEAL CLOCKS ON THE SHUTTLE (H = 325 KM, E = 0 AND E = 0.01) AND ON THE GROUND (H = 0.58 KM ABOVE SEA LEVEL FOR AN OBLATE EARTH).

Fig. 19 - Relativistic-effect

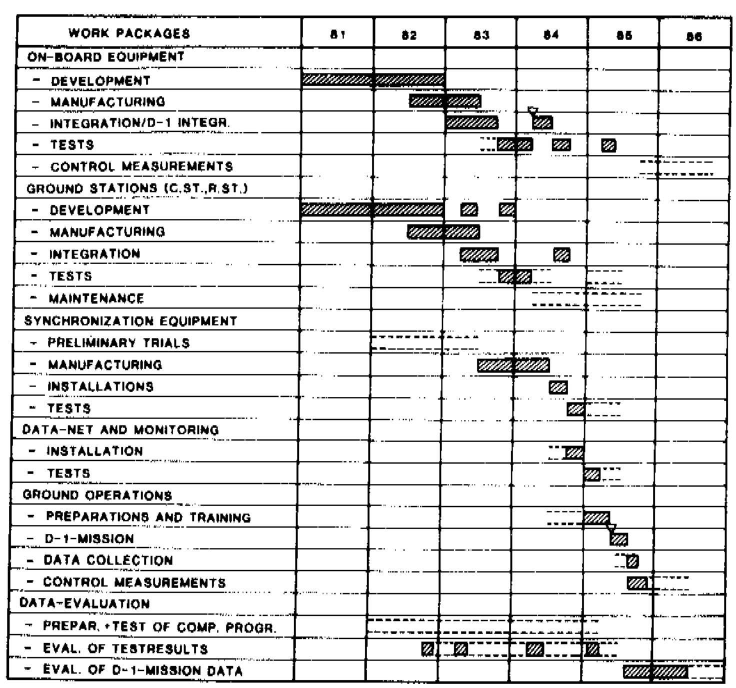


Fig. 20 - NAVEX-Time Schedule

QUESTIONS AND ANSWERS

DR. WINKLER:

Can it be in 10 parts? There has been such smorgasbord of interesting details that I think there are several questions.

Number one, what kind of a clock do you use now? In, yes, your master clock?

MR. STARKER:

We have a cesium clock from Hewlett-Packard.

DR. WINKLER:

Regular or high performance?

MR. STARKER:

High performance tube.

DR. WINKLER:

And in your interesting straight-line comparison between our clock and yours, over ten days, what have been the residuals?

MR. STARKER:

We could only measure the precision, our receiver is not calibrated. And the other is, that we are not sure if this is correct. If it's smaller than 5 nanoseconds, this signal, but over ten days we cannot save a good tape ---

DR. WINKLER:

From the graph, it look like 10 nanoseconds or 15, which is excellent, of course.

MR. STARKER:

Excuse me, my co-author is here, Mr. Nau, who had made these measurements. Perhaps he knows a more exact value.

MR. NAU:

If taken for ten days, we have a one sigma value for a single point for less than twenty nanoseconds.

PROFESSOR ALLEY:

Do you intend to fly the Hewlett-Packard cesium standards?

MR. STARKER:

No, this will be another clock. A cesium clock and a rubidium clock. We hope to get it from the United States, and from a company which has experience with phase one clocks.

PROFESSOR ALLEY:

Do you intend to keep the clocks running during the launch and landing?

MR. STARKER:

At first we intended to do so but Nau did not agree and we must switch it on, we are sorry.

PROFESSOR ALLEY:

So am I. Thank you.

MR. STARKER:

Thank you very much.