NASA TM X- 66001

ATS C-2 SATELLITE VLBI EXPERIMENT

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JUNE 1972

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GREENBELT, MARYLAND

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Goddard Space Flight Center

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ABSTRACT

The Geodynamics Branch of the Trajectory Analysis and Geodynamics Division submits this proposal to conduct a Satellite VLBI Experiment using the planned ATS C-2 spacecraft. The main objectives of the experiment are: (i) Precision spacecraft position determination with the VLBI technique and comparison of the L-band interferometric technique with the L-band R and $\dot{R}$ technique from the viewpoint of operational simplicity and precision, (ii) comparison of the "single differential doppler" and the wideband VLBI technique for such uses as tracking, geodesy, etc., (iii) derivation of real-time ionospheric corrections and phase-scintillation effects utilizing simultaneous 2-frequency (L- and C-band) tracking of the spacecraft in both time-delay and doppler interferometry, (iv) development of techniques for precise time dissemination, particularly to marine users, through wideband time-delay interferometry, (v) development of techniques to use synchronous satellites as stable platforms in space for future work in the area of "marine geodesy," (vi) station location and calibration, (vii) aid to L-band navigation experiments which utilize precise spacecraft position and time in deriving user's position.

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I. SATELLITE VLBI EXPERIMENT

The Geodynamics Branch [Code 553] of the Trajectory Analysis and Geo-dynamics Division submits this proposal to conduct a Satellite VLBI Experiment using the planned ATS C-2 spacecraft. The experiment will be referred to as the VLBI experiment in this document. Dr. J. Ramasastry is the proposed Principal Investigator of the experiment. Coinvestigators for this experiment will be selected later.

II. OBJECTIVES & JUSTIFICATION

The following are the main objectives of the experiment:

a. Precision determination of spacecraft position in three dimensions to better than 10 meters with the VLBI technique and comparison of the L-band interferometric technique with the L-band R and RR technique from the viewpoint of operational simplicity and precision.

b. Comparison of the "single differential doppler" and the wideband VLBI technique for such uses as tracking, geodesy, etc.

c. Derivation of real-time ionospheric corrections and phase scintillation effects utilizing simultaneous 2-frequency (L-band and C-band) tracking of the spacecraft in both time-delay and doppler interferometry.

d. Development of techniques for time dissemination to a precision of 10 nanoseconds particularly for marine users utilizing wideband time-delay interferometry.

e. Development of techniques to use synchronous satellites as stable plat-forms in space for future work in the area of "marine geodesy."

f. Instantaneous relative position of user by L-band navigation to within 1.5 meters.

There are several justifications for the objectives outlined above. Precise knowledge of the spacecraft's instantaneous position is essential to accurate navigation. The navigational error approaches the magnitude of the uncertainty in the spacecraft position at certain user latitudes [Ref: a) Final Report on Satellite Experiments, General Electric Company, MARAD Contract MA-2-4066, July 1972; b) Ranging and Position Fixing Experiments using ATS Satellite, NAS-5-11634, General Electric Company, 1972; c) Private Communication from R. E. Anderson/General Electric Company to Dr. J. Ramasastry/NASA-GSFC, June 1972]. Since one of the objectives of the ATS C-2 Project is to develop a spacecraft position determination technique at L-band, the VLBI system is a strong contender due to its intrinsic capabilities and operational simplicity. Several ranging techniques including PN code ranging and tone ranging in a scintillating, multipath environment are being planned for use in a multilateration mode to determine the spacecraft's instantaneous position. The VLBI system will provide useful results to compare the relative accuracies of the several systems involved in determining the spacecraft's position in a field-environment.

The VLBI technique can determine the offset of a master clock with a resolution better than 10 nanoseconds. The clock correction can then be coded and made available to the users for calibrating their systems. Time dissemination plays an important role in any navigation/surveillance operation.

Information on ionospheric scintillation at L-band is necessary for developing an optimum design of suitable navigational hardware on user crafts. Simultaneous L-band and C-band interferometer measurements provide useful data in this regard.

Last but not the least, the VLBI experiment is designed to evaluate the feasibility of satellite-oriented remote-site and marine geodesy. Small portable dishes at remote sites or at sea could be tracked with a three dimensional accuracy of less than 5 meters by using satellite VLBI technique. Of course, this accuracy can be further improved if we are able to develop a better model of the spacecraft's instantaneous motion. It is hoped that the present experiment will provide a breakthrough in this area. The importance of marine- and remote-site geodesy in the NASA Application Program need not be stressed.

III. EXPERIMENT DESCRIPTION

Very Long Baseline Interferometry (VLBI) is a technique in which noise signals from a distant radio source [for example, Geostationary satellites, quasars, radio galaxies, and the like] are received and recorded independently and simultaneously at widely separated terminals. The recordings are then cross-correlated to derive the "interferometric parameters," namely time-delay and fringe-rate. The "time-delay" is analogous to "differential range" and the "fringe-rate" is analogous to "differential doppler." Figure (1) is a schematic diagram of an interferometer pair.

The VLBI system is an arc and arc-rate technique of extraordinary precision. The following table (Table 1) gives the resolution of the arc and arc-rate parameters that have been achieved by us in the past.

A simple rule of thumb for computing the angular resolution of a VLBI system is the parameter $\lambda/3D$ where λ is the wavelength of the radio signal and D is the chord-length between the two terminals.

The time-delay resolution achievable by the Rosman-Mojave baseline using narrowband interferometry (360 kHz bandwidth) is 5-10 nanoseconds [Ramasastry et al., 1972]. With wideband interferometry where a much larger noise signal bandwidth (of the order of 10 to 20 MHz) is sampled, the time-delay resolution achievable is of the order of less than a nanosecond. It should then be possible to determine the spacecraft position (x, y, z) to within 50 meters consistently. In the past, our best results were 70 meters.

In addition, a new technique called the "single differential VLBI doppler [SDVD] technique" will be used to derive the fringe-rate data directly. In this technique, the stations involved receive a monochromatic signal from the spacecraft and sample the N-count (Doppler) at a rate of ten samples/sec. The differential N-count between the two stations directly yields the fringe-rate obtained in VLBI.

Several uses may be made of the data:

a) Through the determination of the doppler fringe-rate of the interferometric signal derived from two or more simultaneously receiving stations and augmented by the differential delay between the two station-spacecraft paths, an orbital model can be formed which can be increasingly refined by a larger number of observations and by the addition of another independent baseline.
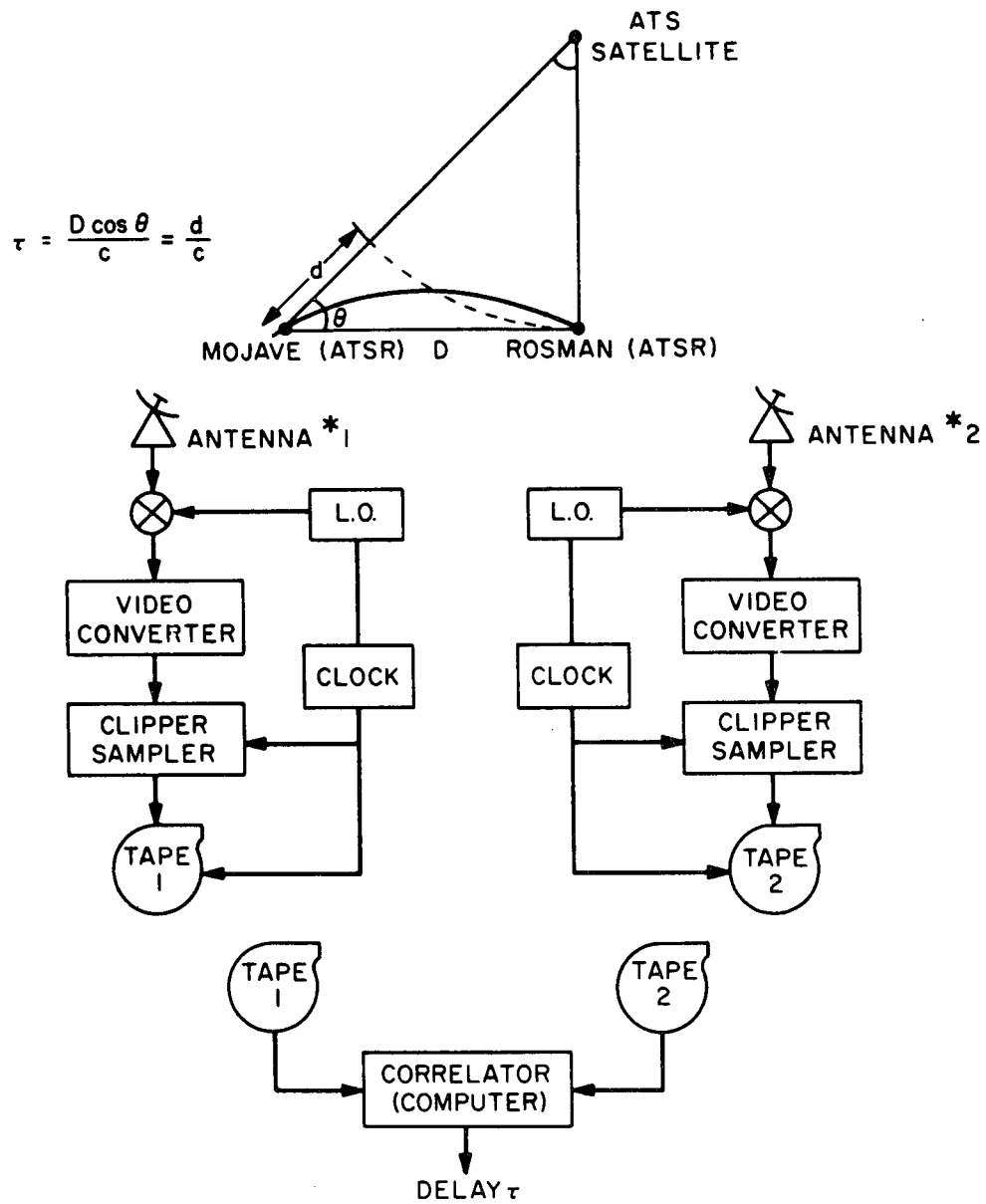
Figure 1. VLBI schematic diagram.

Table 1
VLBI Tracking Parameters

Tracking Parameter	Resolution
Angle ($\Delta\theta$)	5×10^{-9} radians
Arc ($\Delta S = R\Delta\theta$)	< 1 meter
Angle-rate ($\Delta\dot{\theta}$)	10^{-11} radians/sec
Arc-rate ($R\Delta\dot{\theta}$)	0.1 mm/sec

b) Further, if the fundamental measurement of the angles between the base-lines of the observing stations and the line-of-sight to the satellite is combined with a single-range to the satellite, then it is possible to compute the absolute position of the satellite to great precision. Conversely, if the satellite position is precisely known, the station coordinates can be accurately determined in a general solution.

The determination of the satellite-baseline angle is most accurately done by increasing the bandwidth of the interferometers. This is evident from the following expression for the time-delay resolution:

$$\sigma_{\Delta\tau} = \frac{1}{2\,\pi\,(BW)\left(\frac{S}{N}\right)^{1/2}} \qquad *$$

where (BW) is the recording bandwidth and S/N is the signal to noise ratio. Also

$$\Delta\tau = \frac{1}{2\,\pi\,f_c}\,\Delta\phi$$

f_c being the RF-band center frequency, and

$$\Delta\phi = \frac{2\,\pi\,D}{\lambda}\,\sin\Delta\theta$$

---

*For derivation see Ramasastry et al., "VLBI Tracking of ATS Satellites," GSFC X-553-72-290, 1972.

where

> θ is the baseline-source angle
>
> λ is the signal wavelength

and

> D is the baseline chord length.

Therefore, an increase in the bandwidth of the correlated signals linearly increases the measurement precision of θ.

A secondary output of the wideband VLBI correlator is the fringe-rate (differential doppler) between the stations. However, since the doppler can be more economically extracted from a monochromatic signal using the previously mentioned SDVD technique, this processing will not be done in the proposed experiment except as a means of comparing the performance of the two modes of tracking.

IV. PROPOSED EXPERIMENT PLAN

a) L-band and C-band wideband noise from the spacecraft [either the spacecraft front-end noise or the ground transmitted noise cross-strapped at the spacecraft] will be recorded at 2 or 3 ground stations simultaneously and separately. The received noise signals are SSB detected, coherently down-converted to video, clipped/digitized and sampled and recorded on video tape using a video-tape recorder at a basic bit rate of 2 megabits/sec. A large noise signal bandwidth ($\sim$ 20 MHz) is sampled by sequentially switching the first L.O. frequency of the VLBI video converter. This is done to synthesize a large bandwidth and circumvent the drawback caused by the nonavailability of wideband video tape-recorders. The data tapes from the ground stations are shipped to GSFC for processing using wideband correlators. The data will be processed to derive the differential time-delay and fringe-rate as a function of time. This data is then used in orbit determination, time dissemination, ionospheric time-delay correction and other analyses. Wideband VLBI data will be used to derive a precision "grid" system for global "time dissemination."

b) Secondly, a monochromatic signal will also be transmitted from the spacecraft at both L-band and C-band simultaneously. These signals are received at the ground stations which will extract the doppler from them (N-count technique) and sample the data at a rate of 10 samples/sec. The doppler N-count data is recorded on paper tape. The N-count data from pairs of stations will be processed to derive the differential N-count or the differential doppler. This is the fringe rate in VLBI terminology. The data will then be used to derive spacecraft orbital parameters, clock drift-rates, ionospheric phase distortion applicable to L-band navigation data, etc.

V. SIGNAL REQUIREMENTS

The essential function of the spacecraft equipment needed by the SAVE experiment proposal is to provide a wideband noise signal centered on each of the nominal L and C-band downlinks. In addition, a sinusoidal carrier component or range-rate sidetone must be simultaneously present in the downlink bands. The wideband Gaussian noise will serve as the VLBI signal and the sinusoidal baseband component will be used to extract doppler directly by coherent comparison with a precise frequency reference.

Experience in modeling and receiving a variety of VLBI noise signals in tracking the ATS satellites (ATS-3 and ATS-5) has shown that the spacecraft noise mode, in which the input channel noise randomly distributes the carrier power over the downlink channel, is satisfactory for wideband VLBI work. The received power level (at least -85 dbm into the VLBI video converter) is adequate and the power is sufficiently uniform over the passband. The 20 MHz bandwidth of the L and C-band links is sufficient to produce a time-delay resolution of the order of a nanosecond using the ATSR ground equipment and our VLBI backend units.

In addition, it is desirable to have the capability of transmitting a local doppler reference frequency to the satellite at L-band and receiving it at the ground stations at both L and C-bands. This signal will serve as a calibration of the entire transmission link and processor, and remove variations between the satellite frequency sources.

VI. DOWNLINK WAVEFORM CONSTRUCTION

The signal spectra required for the VLBI data processing consist of an isolated stable sidetone and a constant density noiseband of approximately 20 MHz bandwidth. The relationship of these signals at the input of the downlink upconverter is shown in Figure (2). The doppler reference sidetone is attenuated below the noiseband drive level to insure that intermodulation products generated in the passband will not have a significant effect on the density of the 20 MHz noiseband.

The various signal components are tabulated in Table 2 showing which channels they may occupy during the experiment.

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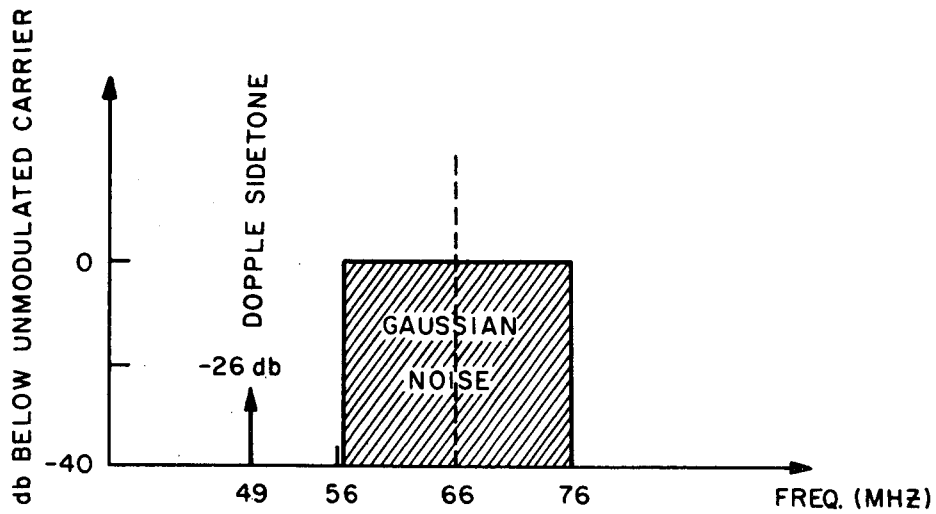
Figure 2. Downlink waveform diagram.

Table 2
Data Signal Components

No.	Item	C-band downlink	L-band downlink	L-band uplink
1	20 MHz noiseband	X	X	–
2	Satellite doppler sidetone (BCN signal)	X	X	–
3	Calibration doppler sidetone (station reference)	X	X	X
4	Doppler Product	X	X	X

The usual downlink signal at each frequency can be expressed as

$$
\int_{\substack{\text{TOTAL} \\ \text{DOWNLINK}}} = \int_{\substack{\text{NOISE} \\ \pm\text{DOPPLER}}} + \int_{\substack{\text{Satellite} \\ \text{Sidetone}\pm\text{Doppler}}} + \int_{\substack{\text{Calibration} \\ \text{Sidetone}\pm\text{Doppler}}}
$$

However, in the usual mode of operation, either the satellite sidetone or the calibration sidetone will be present in the downlink.

VII. SPACECRAFT EQUIPMENT

The several signals described above may be implemented using existing hardware and, for the most part, existing equipment locations in the spacecraft.

Discussions with the Communications Research Branch [Private Communications: James Brown] confirms that the L-band repeater master-oscillator and MO amplifier multiplier that are presently in the spacecraft can be used to drive a beacon amplifier and X3 multiplier module. The output of this module which must be installed is then attenuated and split to the limiter-amplifier in both the C- and L-band upconverter circuits. The master oscillator thus provides the doppler reference sidetone to both L and C-band downlinks. Figure (3) shows the method proposed for generating the doppler beacon sidetone. Switching of the sidetone can be done by ground command.

The arrangement shown in Figure (3) permits generation of the desired spacecraft noiseband (front-end noise) together with the doppler beacon. In normal operation, the doppler beacon is not coherent with the C-band master oscillator (MO) since it is generated by the L-band MO. To calibrate out the frequency difference between the two channels and to test the ATSR processor, a reference doppler sidetone will be transmitted to the spacecraft on the L-band uplink and (1) retransmitted on L-band downlink (2) cross-strapped to C-band and retransmitted also at C-band. Comparison of the processor (Doppler extractor) outputs at both bands will resolve any discrepancies between the two spacecraft crystal oscillators.

When no external inputs are present at the limiter amplifiers of both channels, a noiseband signal will be generated and transmitted in each channel, which it will share with the doppler beacon signal as shown in Figure (2). Removal of external inputs to the limiter is done by ground command. The noiseband signal does not require any modification of existing spacecraft equipment, design or procedures.

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L-BAND LINK

148
VCO

FROM ANTENNA ELECTRONICS → ATTEN-UATOR → INTER-AMPL (134) → POST AMPL (138) → LIMITER/AMPL → TO L-BAND UPCONVERTER

L-BAND UPCONVERTER ← MASTER OSC

(DOPPLER SIDETONE NONCOHERENT WITH C-BAND MASTER OSCILLATOR)

C-BAND LINK

VCO

CROSS-STRAP → POST AMPL → LIMITER/AMPL → TO C-BAND UPCONVERTER

(DOPPLER SIDETONE COHERENT WITH C-BAND MASTER OSCILLATOR)

x 4 | x 4 | POWER-SPLIT (142) → BCN AMPL x 3 → ~ 49.74510 MHz → ATTEN-UATOR

LIMITER/AMPL → TO REDUNDANT L-BAND UPCONVERTER
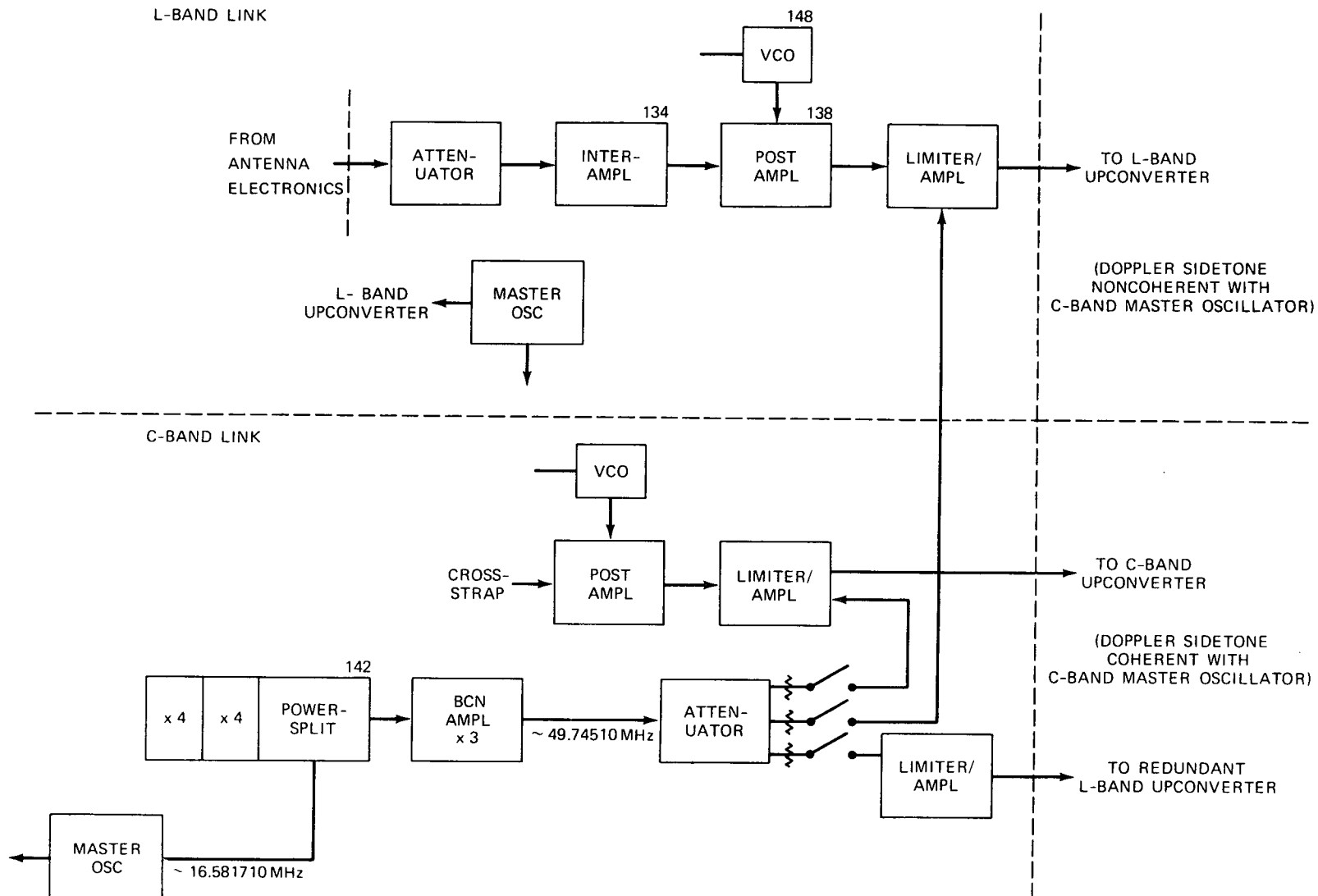
MASTER OSC → ~ 16.581710 MHz

Figure 3. Spacecraft configuration showing modifications for VLBI doppler sidetone transmission.

VIII. GROUND STATION REQUIREMENTS

It is planned to use the C- and L-band ground station facilities at Rosman and Mojave. It is also planned to use the ATSR facility (SHF only) at Kashima at some stage of the experiment. The Agassiz Radio Observatory which has both C-band and L-band receivers that are comparable with the ATSR system will be used during the experiment. The Agassiz station is located in Harvard, Massachusetts and belongs to the Smithsonian Astrophysical Observatory.

Antennas and Receivers: The following table lists the various antennas and receivers that are planned for use.

Table 3
Antennas and Receivers

Station	C-band	L-band	Mode
MOJAVE ATSR	40' Dish & Receiver	15' Dish & Receiver	Simultaneous or Separate
ROSMAN ATSR	85' Dish & Receiver	15' Dish & Receiver	Simultaneous or Separate
AGASSIZ Station	84' Dish & Receiver	84' Dish & Receiver	Either C-band or L-band at a time
KASHIMA ATSR Japan	85' Dish & Receiver		Optional Use

Figure (4) is a schematic diagram of the ground station setup for the wideband VLBI recording at C-band. A similar setup for L-band recording is shown in Figure (5). As may be seen in the diagrams, the VLBI backend is to be furnished by the experimenter. The remaining equipment is a part of the ATSR SHF and L-band receiver systems. These systems have been used by us in the past [Ref: (1) VLBI Experiments using the ATS-1 and ATS-3 Satellites, J. Ramasastry et al., NASA/GSFC X-550-70-432, November, 1970; (2) Precision Tracking of the ATS-3 Satellite Using the VLBI Technique, J. Ramasastry et al., 52nd Annual Meeting of the American Geophysical Union, Washington, D.C., April 21, 1972].

Video tapes [2' wide, 10.5" diameter, 2400' length reels] are required for recording the wideband VLBI data. 7-Track/9-Track digital magnetic tapes are used during cross-correlation of data at GSFC.

Figure 4. Wideband VLBI ground station set up for C-Band.
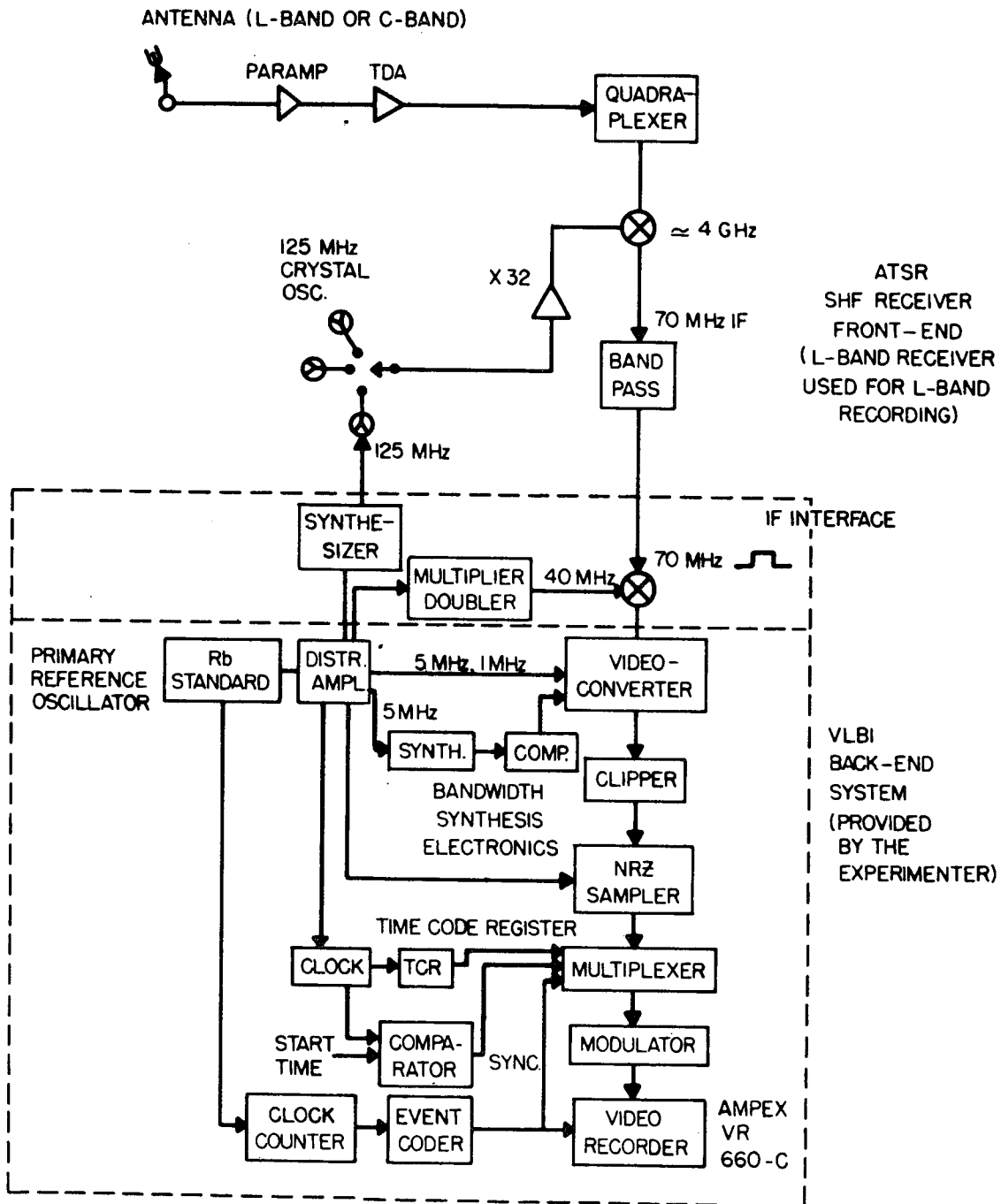
NOTE: L-BAND RECEIVER FRONT END CIRCUITRY IS DIFFERENT FROM THE SHF CIRCUITRY

Figure 5. Wideband VLBI ground station set up for L-Band.

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Two VLBI backends (one for C-band recording and one for L-band recording) are needed per station. As shown in diagrams 4 and 5, a VLBI backend consists of the following items:

(i) Video converter
(ii) Clipper/sampler
(iii) Bandwidth switching electronics
(iv) Two HP-synthesizers 0-125 MHz, 0.50 MHz
(v) VLBI Frequency Standard. Also called Reference Oscillator. A rubidium standard is normally used.

The experimenter will take the responsibility for the installation and operation of the VLBI system. The ATS C-2 Project is requested to discuss with us financial matters and installation problems. In the past the VLBI backends that belong to the experimenter have been installed (and later removed) during VLBI experiments with the ATS-3 satellite. Equipment to be installed and operated at the SAO Agassiz station is the sole responsibility of the experimenter.

IX. GROUND STATION SUPPORT

The experimenter and his representatives will provide close support during all phases of the experiment. Any instrumental problems in the VLBI system will be attended to by the experimenter. Normal experiment scheduling and data-acquisition support is requested.

X. SCHEDULE

The experiment will be performed on a non-interference, time-available basis. The priorities setup by the ATS C-2 Project in scheduling the experiments will be strictly adhered to. Any special scheduling requests will be made in writing or TWX to the ATS C-2 Control Center.

XI. REPORTS

Results and reports of the experiment will be forwarded to the Project in the usual manner

XII. REFERENCE

Ramasastry, J. and B. Rosenbaum, Tracking of the ATS-3 Satellite by the Very Long Baseline Interferometer Technique, AGU Meeting, Washington, D. C., April 1972.
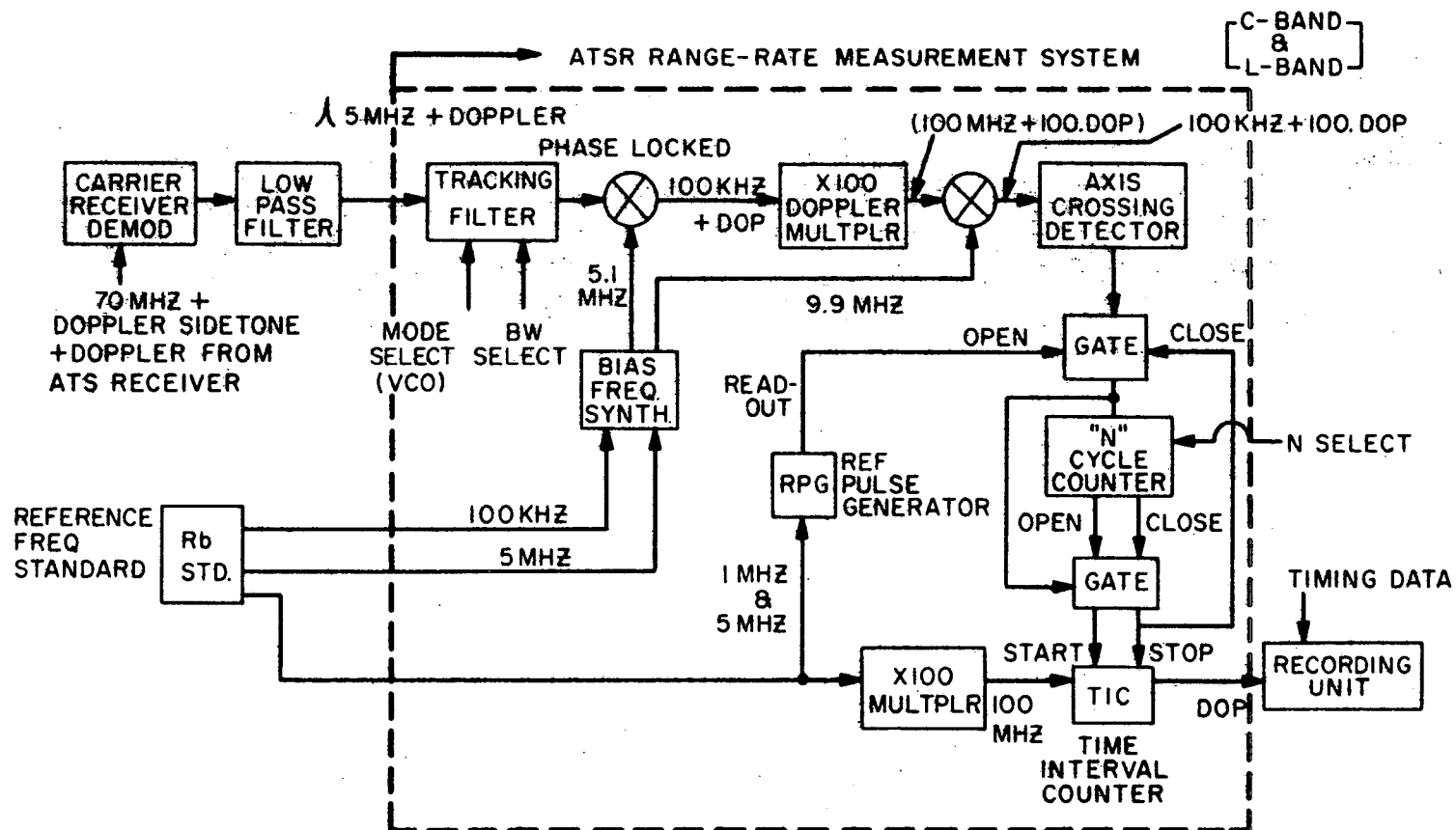
Figure 6. C-Band (or L-Band) doppler extractor set up.

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Final Report on Satellite Experiment, General Electric Co., Marine Administration MA 2-4066, July 1972.

APPENDIX

VLBI DATA RETRANSMISSION EXPERIMENT

From the operational point of view, one of the drawbacks of the VLBI technique is the time-consuming logistics involved in transferring the VLBI data tapes from remote sites to a central processing facility where data-tapes from pairs of stations are suitably formatted and cross-correlated. This is not an attractive procedure if the intention is to utilize the VLBI technique for operational spacecraft tracking and position determination. This drawback can be overcome by retransmitting VLBI data from remote sites to a master station via synchronous satellites and cross-correlating the data at the master station using small special purpose correlators. The preprocessed data can then be transferred to the central processing facility via teletype for post-processing, orbit-determination and a variety of scientific investigations.

It is with this objective in mind that it is planned to conduct preliminary data transmission tests during some phase of our experiment plan in the VLBI proposal. If the tests are successful, it is planned to utilize this feature as a part of SAVE data-processing provided ground station and satellite schedules permit such an operation. If it is not possible to utilize this feature all the time, data-transmission via satellites shall be conducted whenever possible and utilize conventional data-handling and processing procedures during the remainder of the time. Therefore, data retransmission experiment should be treated as an option in the VLBI proposal.

Figures (A-1) and (A-2) depict the two different data processing systems that can be used. Figure (A-1) describes the conventional data processing procedure while Figure (A-2) shows how the procedure is altered when data retransmission via satellites is utilized.

Figures (A-3) and (A-4) show the uplink (for the station transmitting the data) and downlink (for the station receiving the data) configurations of the ground stations for the data retransmission experiment. The following points are considered in designing the configuration.

a) Systems shown are calculated to produce 20 dB carrier to noise ratio. Bit error probability is 10^{-6}.

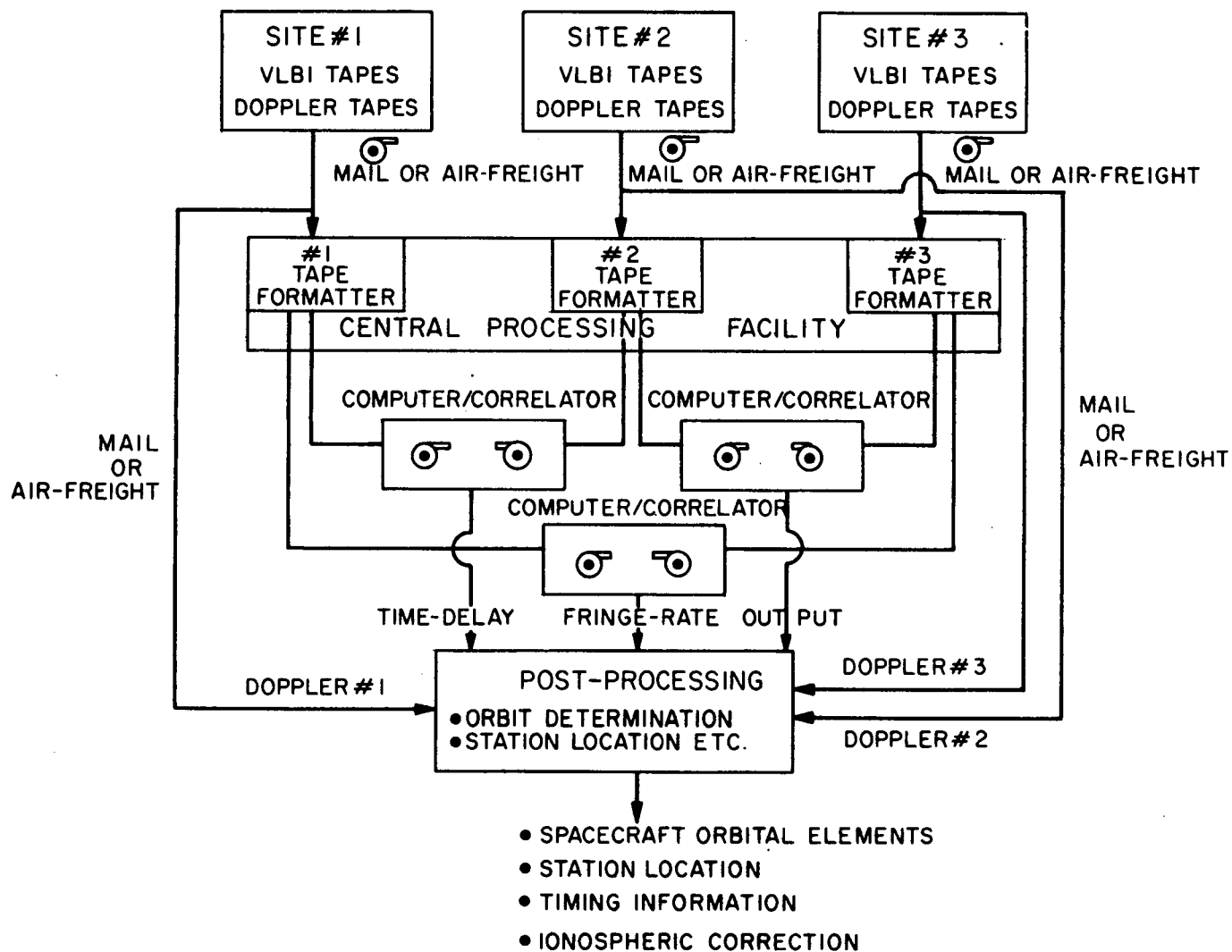b) Data rate is 720 kbits/sec. Recording on video tape is bipolar.

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Figure A-1. Conventional data-processing schematic.

MASTER STATION

| STATION #1 |
| VLBI DATA |
| DOPPLER DATA |

| STATION #2 |
| VLBI DATA |
| DOPPLER DATA |

| STATION #3 |
| VLBI DATA |
| DOPPLER DATA |

RECORDERS

FORMATTERS

DATA RETRANSMISSION
VIA
SYNCHRONOUS SATEUITE

SPECIAL
PURPOSE
CORRELATORS

PREPROCESSED
VLBI DATA
TELETYPE

CENTRAL-PROCESSOR

POST-PROCESSING
ORBIT DETERMINATION
ETC.

TELETYPE

DOPPLER DATA

ORBITAL ELEMENTS
STATION LOCATIONS
TIMING INFORMATION
IONOSPHERIC CORRECTION
ETC.

Figure A-2. New data-processing concept using data retransmission technique.

MODIFIED
VIDEO RECORDER

VIDEO OUT

720K BITS/
SEC

PLAYBACK OF
RECORDED VLBI DATA

BIPOLAR
TO
NRZ OR
MANCHESTER
CONVERTER

★

BALANCED
DRIVER

RAYHEON FM (FSK) TRANSMITTER

AMPLIFIER/
LIMITER

MIXER

MODULATOR

MODULATOR DRIVER

AFC
LOCKED
LOOP

LOCAL
OSCILLATOR

84' DISH

L.O.(FT-70 MHZ)

6120 MHZ

MIXER DRIVER

POWER
AMP

GAUSSIAN
FILTER ★

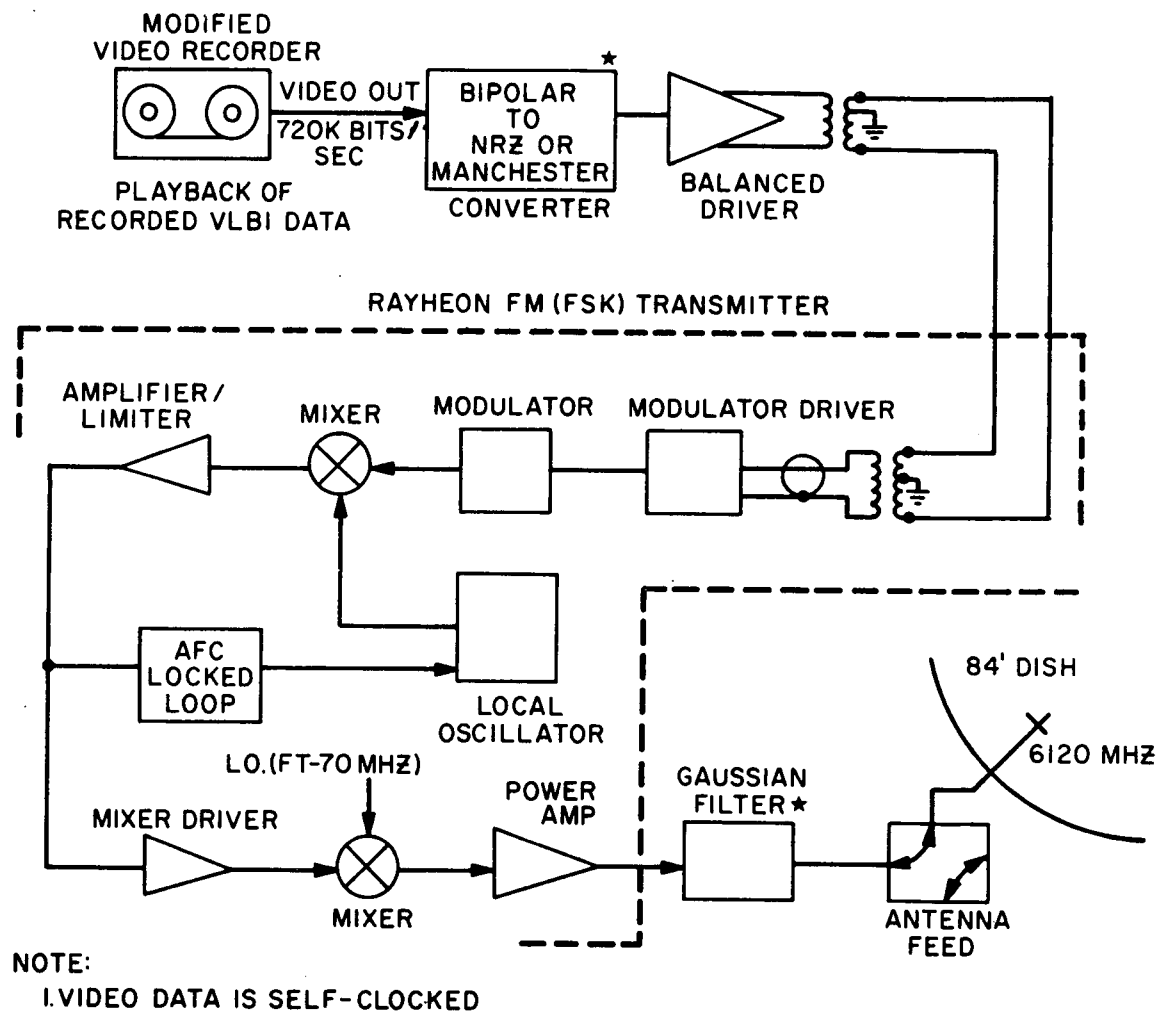MIXER

ANTENNA
FEED

NOTE:
I.VIDEO DATA IS SELF-CLOCKED

Figure A-3. VLBI data retransmission experiment-uplink.

Figure A-4.   VLBI data retransmission experiment-downlink.

c) Downlink recorder format is compatible (upon playback on digital recorder) with the VLBI systems that use digital recorders (for example, IBM TM-16) for recording the VLBI data.

d) Alternative receiver could use matched filters plus bit synchronized sampling and decision circuitry.

e) Boxes matched by asterisk (*) are not presently available at the ATS ground stations and probably would have to be constructed.

f) Modified video-recorders are identical to present VLBI units except for adjustment of the servophase of the downlink recorder.

g) Unlike the case of VLBI data recording, coherency of local oscillators is not critical.