SATELLITE TIME TRANSFER VIA TDRSS AND APPLICATIONS

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ABSTRACT

In the early 1980's NASA will enter a new era of space program, i.e., space transportation through Space Shuttle. It will have a new large scale space communication system for satellite tracking and data transmission known as the Tracking and Data Relay Satellite System (TDRSS). With two geosynchronous relay satellites TDRSS can provide nearly worldwide coverage for communication between all near orbiting satellites and the satellite control center at Goddard Space Flight Center. Each future NASA satellite will carry a TDRSS transponder with which the satellite can communicate through a TDRS to the ground station at White Sands, New Mexico. It is using this system that the ground station master clock time signal can be transmitted to the near earth orbiting satellite in which a clock may be maintained independently to the accuracy required by the experimenters. This paper presents the satellite time transfer terminal design concept and the application of the time signal in autonomously operated spacecraft clock. Some pertinent TDRSS parameters and corrections for the propagation delay measurement as well as the time code used to transfer the time signal will be given.

INTRODUCTION

The use of satellites for time transfer began soon after the first artificial satellite was placed in orbit. This was because the concept as well as the instrumentation design was simple. It was done as an experiment to demonstrate the capability in precision over long range and the favorable geometrical configuration for the signal to propagate through the medium. In comparison with the terrestrial propagated signal, the signal transmitted from or transponded by a satellite is relatively independent of the propagation medium. The stated precisions by investigators in the last two decades using different carrier frequencies, techniques, and satellites shows orders of magnitude of improvement, ranging from microseconds to nanoseconds, over the conventional techniques. Although the capability of precision time transfer using a satellite has been amply demonstrated, the limitation of further improvement still lies on the ability to measure the signal path delay. At present, this limitation is about 30 centimeters or 1 nanosecond.

Fortunately, the technology for the time generation and dissemination has been ahead of or at least in pace with the requirements [1]. As independence for timekeeping becomes an essential requirement for on-board navigation and spacecraft autonomy [2] satellite time transfer becomes a technology that is needed for immediate application. In this paper, I shall describe a particular satellite system through which clock time can be transferred from the ground to the users in satellites in near earth orbit or on the ground. The satellite system is called the Tracking and Data Relay Satellite System (TDRSS) [3].

TDRSS

The TDRSS is a new large scale space communication system to be shared between government and commercial use. It is a new NASA tracking and data acquisition and communication system. It also provides additional capability for growing communication traffic in the private sector. The system consists of 4 geosynchronous relay satellites. The first two are for NASA, the third (the advanced Weststar) is for commercial use, and the fourth is a common spare. The system concept is shown in Figure 1. It is represented by the two NASA geosynchronous relay satellites, 130° apart in longitude, and a ground terminal located at White Sands, New Mexico. The system will be capable of tracking, transmitting data to, and receiving data from user spacecraft over at least 85 percent of the user orbit. The ground terminal at White Sands, New Mexico is shown in Figure 2.

The satellite design is shown in Figure 3. Each satellite generates 1700 watts of electrical power from its solar arrays and transmits and receives in 3 frequency bands (S, C, and K) from 6 antennas, 3 of which are steerable. The weight is 2132 kilograms (4700 pounds) and the size is 17 meters (57 feet) from tip to tip. The satellite will be launched by the Space Shuttle in 1981 and 1982 and will have a lifetime of 10 years.

The steerable S and Ku-Band, 4.9 meter antennas, are used to provide communication service for the single access (SA) users, and the S-band antenna array is used to provide communication service for the multiple access (MA) users. The steerable K-band, 2.0 meter antenna, is for the forward and return communication links between space (TDRS) and the ground terminal. The two TDRS can support up to 4 S-band or K-band single access users (SSA or KSA) and up to 20 MA users.

The advantage of such a space communication system [4] can be seen in the next two figures. Figure 4 shows the present NASA tracking and acquisition network. There are 14 ground stations located throughout the world. Figure 5 shows the post TDRSS NASA tracking data acquisition and communications network. It shows 8 ground stations including the Bermuda station to provide only the launch support. There is a 50 percent reduction in the number of the ground stations which also serves the deep space probes and the highly eliptical orbit satellites.

SATELLITE TIME TRANSFER USING TDRSS

A user configuration of a satellite time transfer system using a TDRS is shown in Figure 6. A master clock is located at the White Sands ground terminal. The user may be mobile, fixed on the ground or in a satellite. The master clock is calibrated via a TDRS to a national time standard such as the National Bureau of Standards (NBS) or the U.S. Naval Observatory (USNO), since the NBS and USNO time scales can be related to each other and to the Bureau International de l'Heure. The user's modes may be MA, SSA, or KSA, and the carrier frequencies for each mode are shown in the table in Figure 6. The satellite coverage for the time users at 5° and 10° elevation viewing angles for TDRSS at 41° west and 171° west is shown in Figure 7.

CONCEPT OF OPERATION

The philosophy of operation is directed toward automation, that is the clock time will be transferred from the White Sands terminal via a TDRS to a user satellite by a command sent from the Project Operations Control Center (POCC) at Goddard, Greenbelt, MD. The propagation delay may be measured by a two-way time transfer technique or maybe calculated based on the position information of the ground terminal and tne two predicted satellite positions, if the calculated delay accuracy meets the time accuracy requirement. The received time signal in the user satellite is measured relative to the on-board clock by a time interval unit. After correction for the signal propagation path delay, the clock error is transmitted via the TDRS to the ground for monitoring and verification. The satellite clock is free running up to a pre-set maximum clock error at which time, by on-board computer program action, a step time or a step frequency correction is made. Should the correction be deleted, a command signal is needed to override the automatic clock correction. After such a command, a new value of the maximum clock error must be re-set if the automatic clock correction feature is to be maintained.

A functional block diagram of the ground station time transfer terminal is shown in Figure 8. The time signal data is divided into two parts. One part contains the grouped parallel binary time code (PB5) [5] which is transmitted as data through telemetry. Only the time unit in the time code that is larger than the propagation path delay is of significance. Thus it is called the coarse time. The other part contains a time epoch sequenced pseudo random noise (PN) code [6] which is transmitted through the range channel or the forward link. It has an ambiguity time of 85 milliseconds. It is to this time data that the propagation path delay corrections must be applied. The data processor is shown at the extreme right of Figure 8. The step time and step frequency corrections are used to maintain the ground station clock to that of a national time standard.

The functional block diagram of a satellite clock system [7] is shown in Figure 9. It is identical to the ground station terminal. The only exception is the Global Positioning System (GPS) receiver. This feature is designed for a user satellite either to use the GPS time signal or to compare the time signals of the GPS and TDRSS time transfer systems.

TDRSS PARAMETERS

For detailed TDRSS parameters, signal characteristics and service capabilities, the readers are referred to the TDRSS Users' Guide which is available on request [8]. Some pertinent TDRSS parameters to satellite time transfers are given in Figures 10 and 11.

TIME SIGNAL CORRECTIONS USING TWO WAY TIME TRANSFER VIA A SYNCHRONOUS SATELLITE

In a two-way time transfer using a geosynchronous satellite, the propagation path delay can be approximated as shown in the upper part of Figure 12. This two-way delay is 46 milliseconds (ms). For simplicity of operation, the PN code period is considered to be longer than the two-way path delay, i.e. 46 ms. Thus 85 ms ambiguity is used for the PN code.

In a satellite-to-satellite time transfer, the relative satellite motion of the two satellites must be considered. Based on past data, the doppler motion for all satellites falls in the range of 6 to 8 KM/S which is equivalent to about 20 to 27 μs/s rate. If the correction for doppler motion is made for 1/4 of a second, the residual error is 5 to 7 μs, as shown in the lower table of Figure 12. If the same correction time of 1/4 of a second is applied for satellite motion in a geosynchronous orbit, the residual error is only 17 to 34 ns.

The propagation delay corrections due to the composite atmospheric medium depends on the assumed atmospheric model, season, and geographical locations. Using the example worked out by David Levine [9] in 1970, as shown in Figure 13, the maximum error is 65 ns at 8 GHz and 70 ns at 2 GHz if the atmospheric correction is not made.

ONE WAY TIME TRANSFER OPTION

For most space science users in the 1980's, the timing requirements are in the range of 10 to 1000 microseconds. To meet these needs, one-way time transfer via a TDRS is an attractive option. This is particularly true if the user satellite can navigate on-board to achieve one kilometer position accuracy. This is based on the capability of TDRSS orbit and position data which can be provided in near real-time as shown in Figure 14. Obviously, this service can be provided to a larger number of users through the multiple access mode.

SUMMARY

TDRSS can be used after 1982 as an operational service to transfer precise time by two-way or one-way technique. Using the two-way technique to measure the propagation path delay, the precision of time transfer, without corrections, can be of the order of hundreds of nanoseconds and with correction to the order of nanoseconds. The precision of one-way time transfer technique is limited by the accuracy of the path delay calculations. This is generally in the order of microseconds.

Potential applications in addition to serving the satellite users are for time comparison among navigation system clocks and the national laboratory primary clocks and for cross-calibration of other equally precise time transfer systems.

As in any system design, the accomplishment is the accumulated results of many research and development programs. The author expresses his appreciation without giving the names of those who have contributed to the satellite time transfer technology.

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[8] "Tracking and Data Relay Satellite System (TDRSS) Users' Guide", Revision 4, NASA/GSFC Report STDN 101.2, Doc. Sec., Code 863.2, Goddard Space Flight Center, Greenbelt, MD

[9] LeVine, David M., "Propagation Delay in the Atmosphere," NASA/GSFC Document X-521-70-404, November 1970.

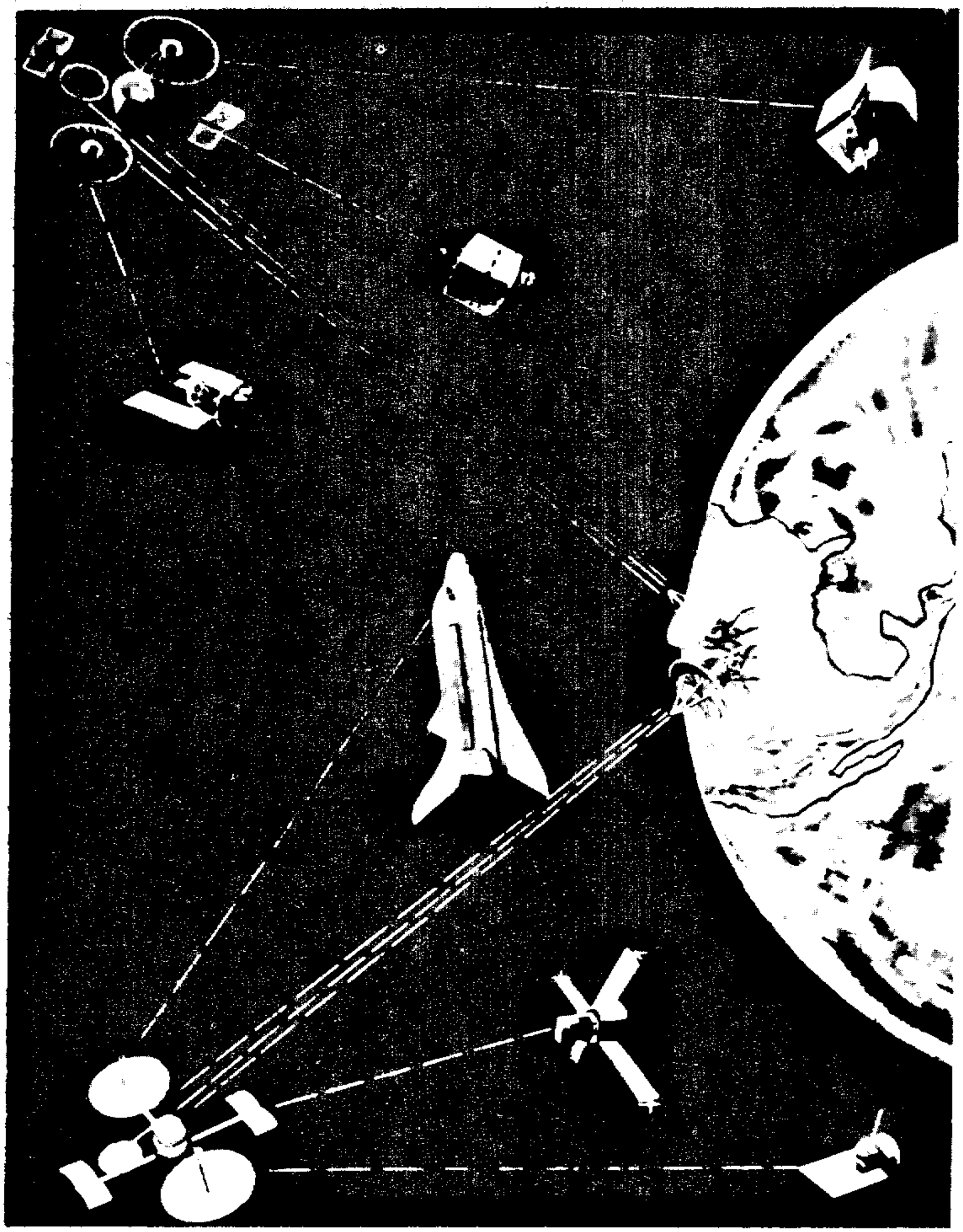


Figure 1. System Concept of the Tracking and Data Relay Satellites (TDRS)

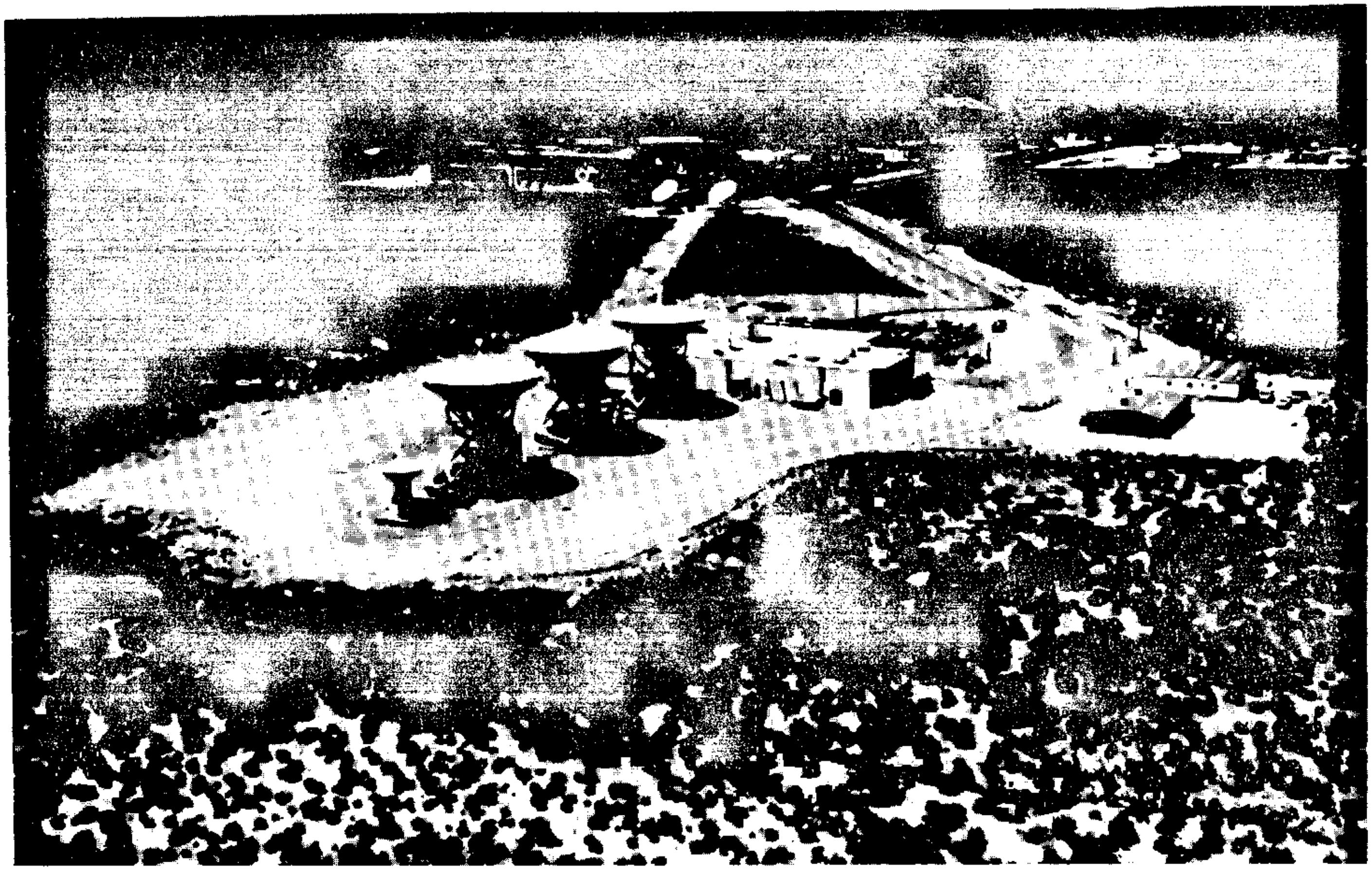


Figure 2. TDRSS Ground Station Communication Terminal, White Sands, New Mexico

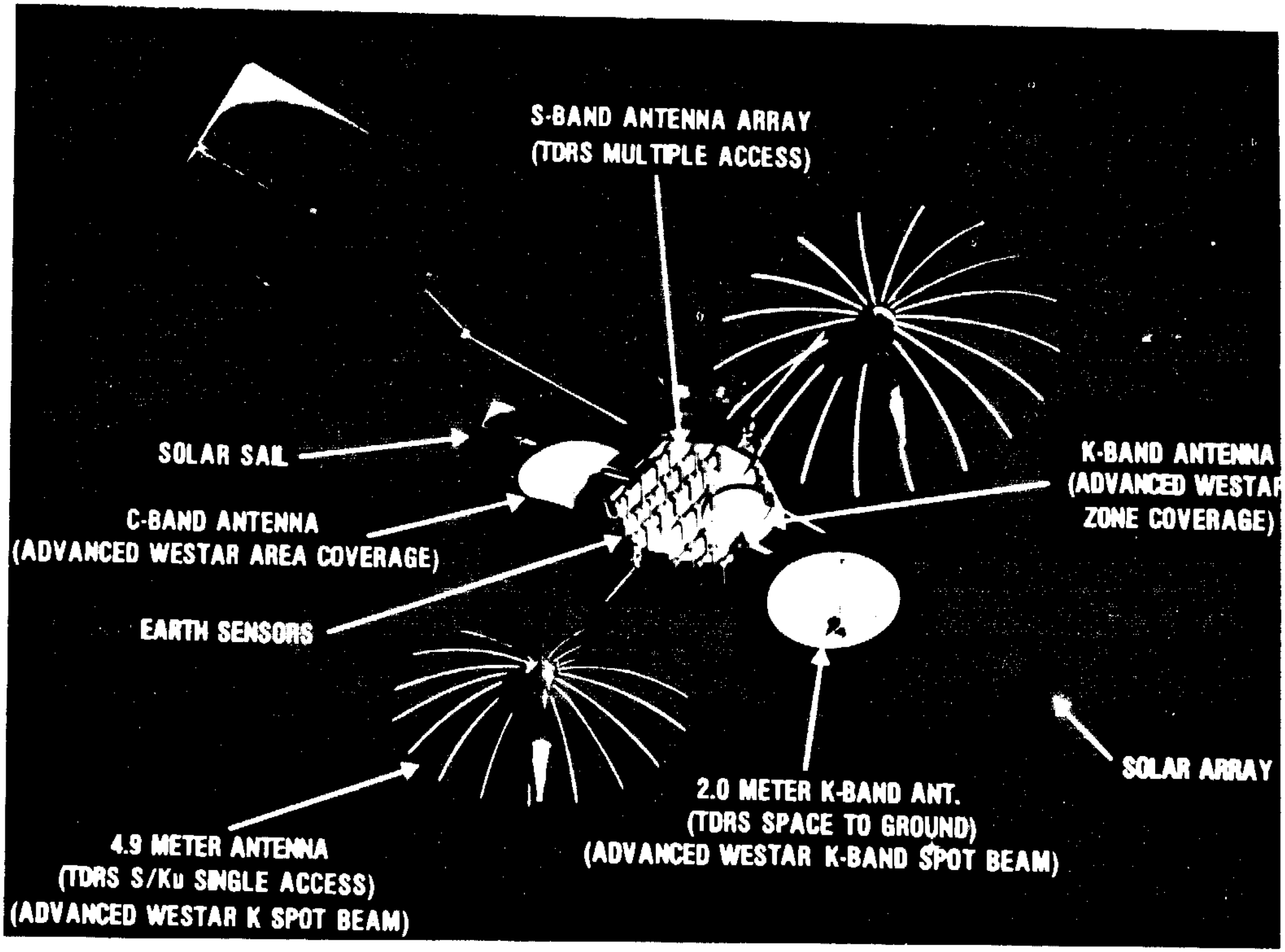


Figure 3. Antenna Design of the Tracking and Data Relay Satellite

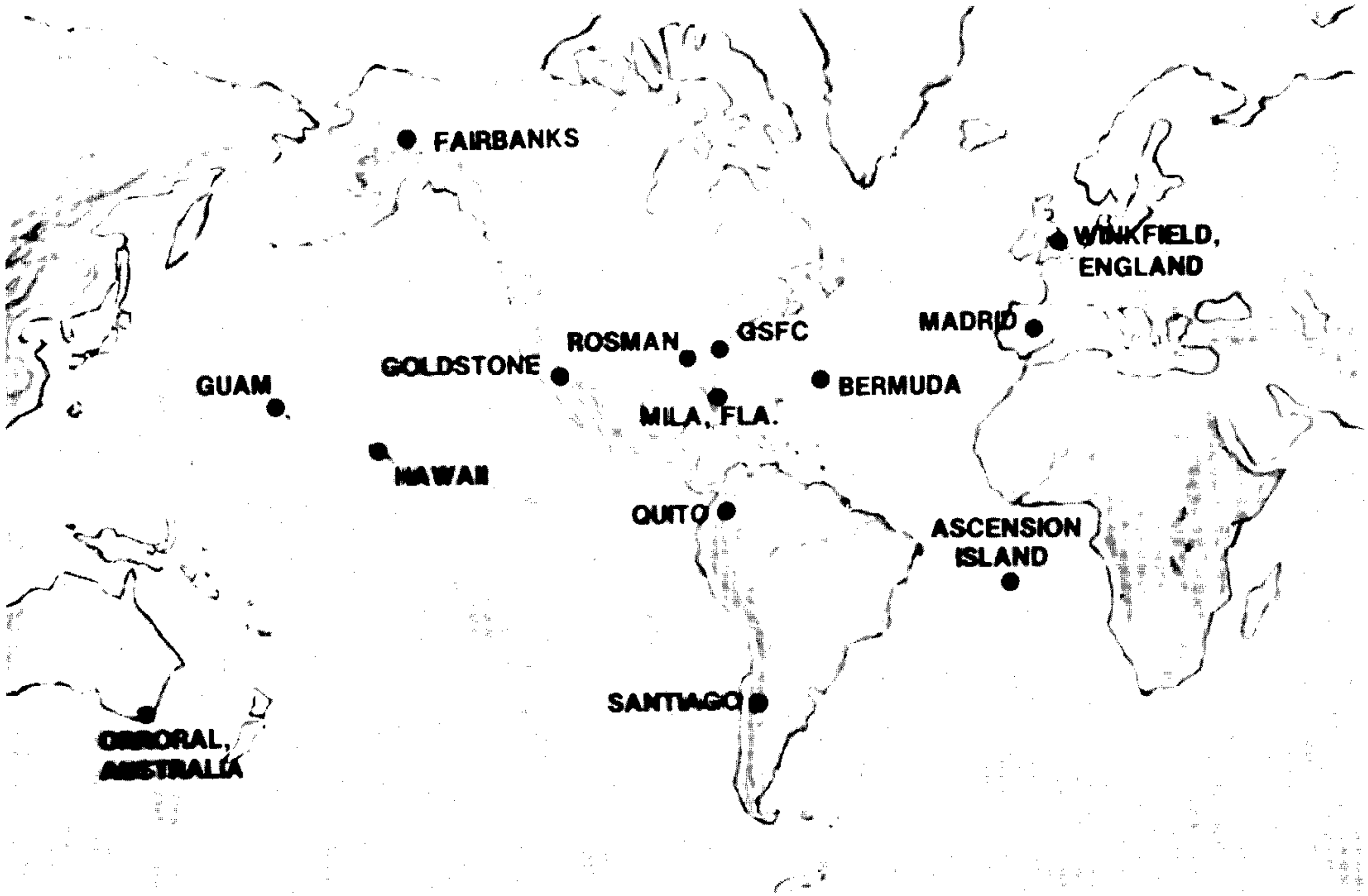


Figure 4. Present NASA Tracking and Data Acquisition Network

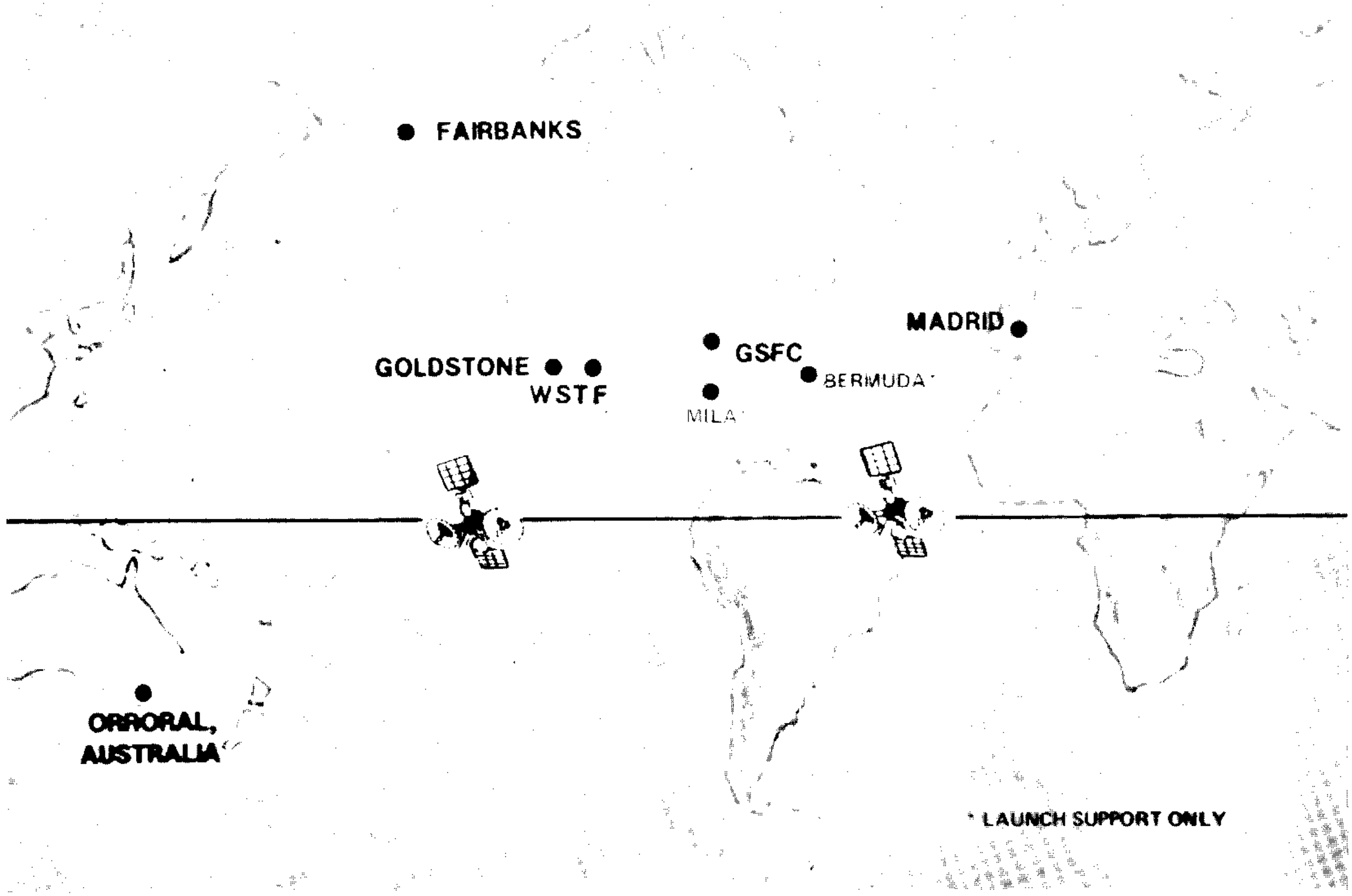
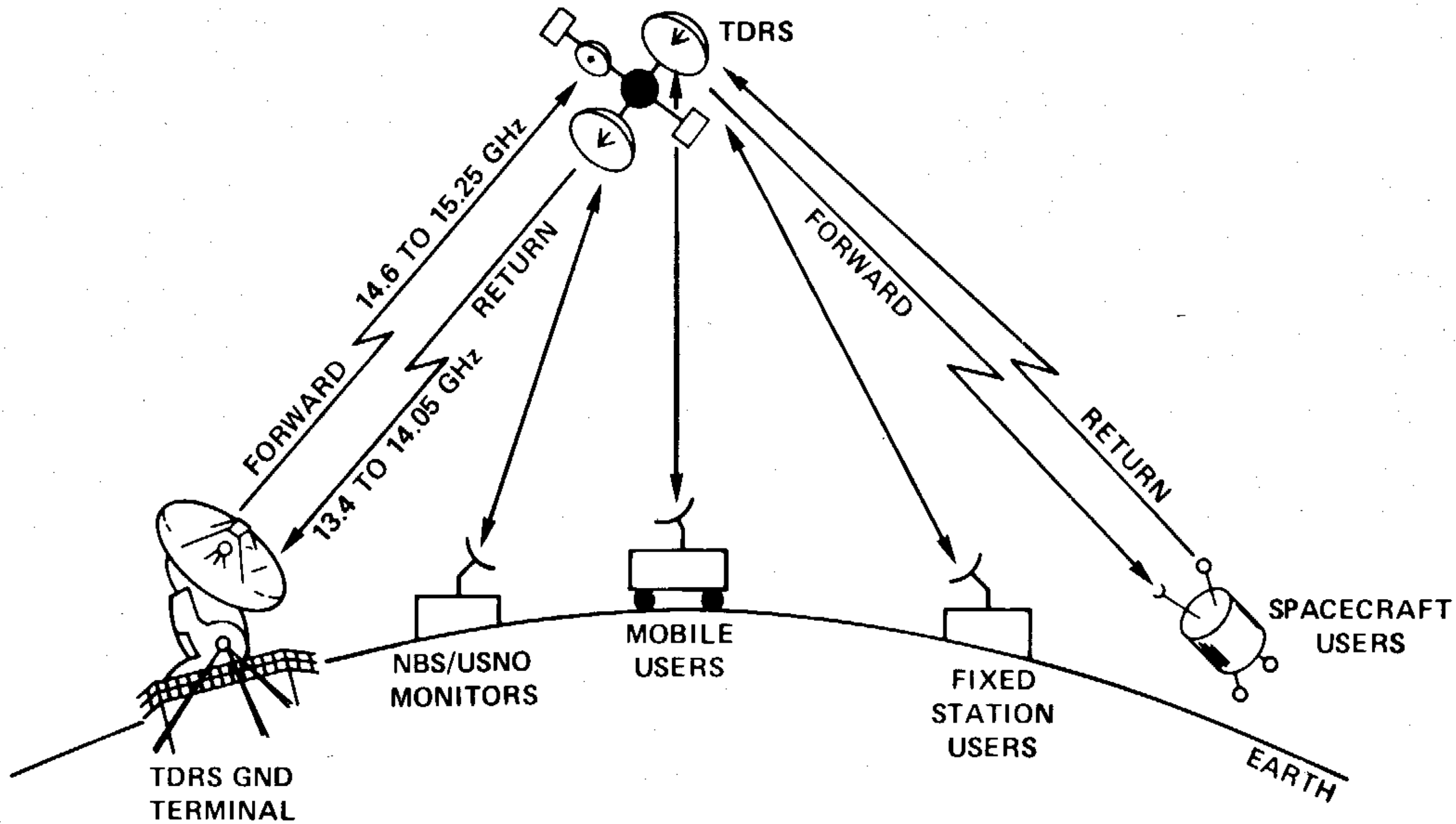


Figure 5. Post TDRSS NASA Tracking, Data Acquisition and Communication Network



USER	MODE	FORWARD LINK		RETURN LINK	
1	MA	2106.14	MHz	2287.5	MHz
2	SSA	2025–2120	MHz	2200–2300	MHz
3	KSA	13.775	GHz	15.0034	GHz

Figure 6. User Configuration of Satellite Time Transfer Using a TDRS

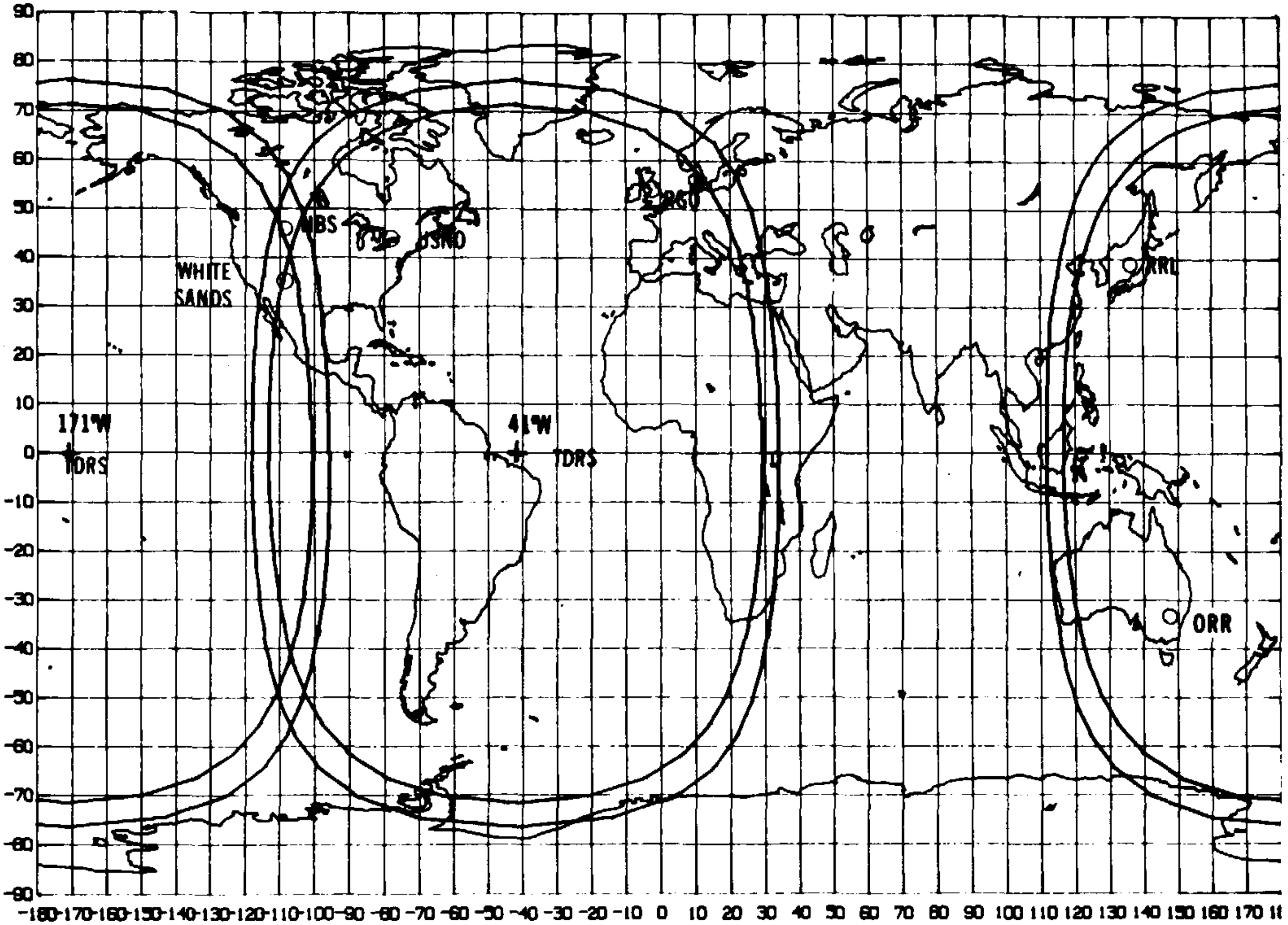


Figure 7. TDRSS Coverage for Time Users at 5° and 10° Elevation Viewing Angles

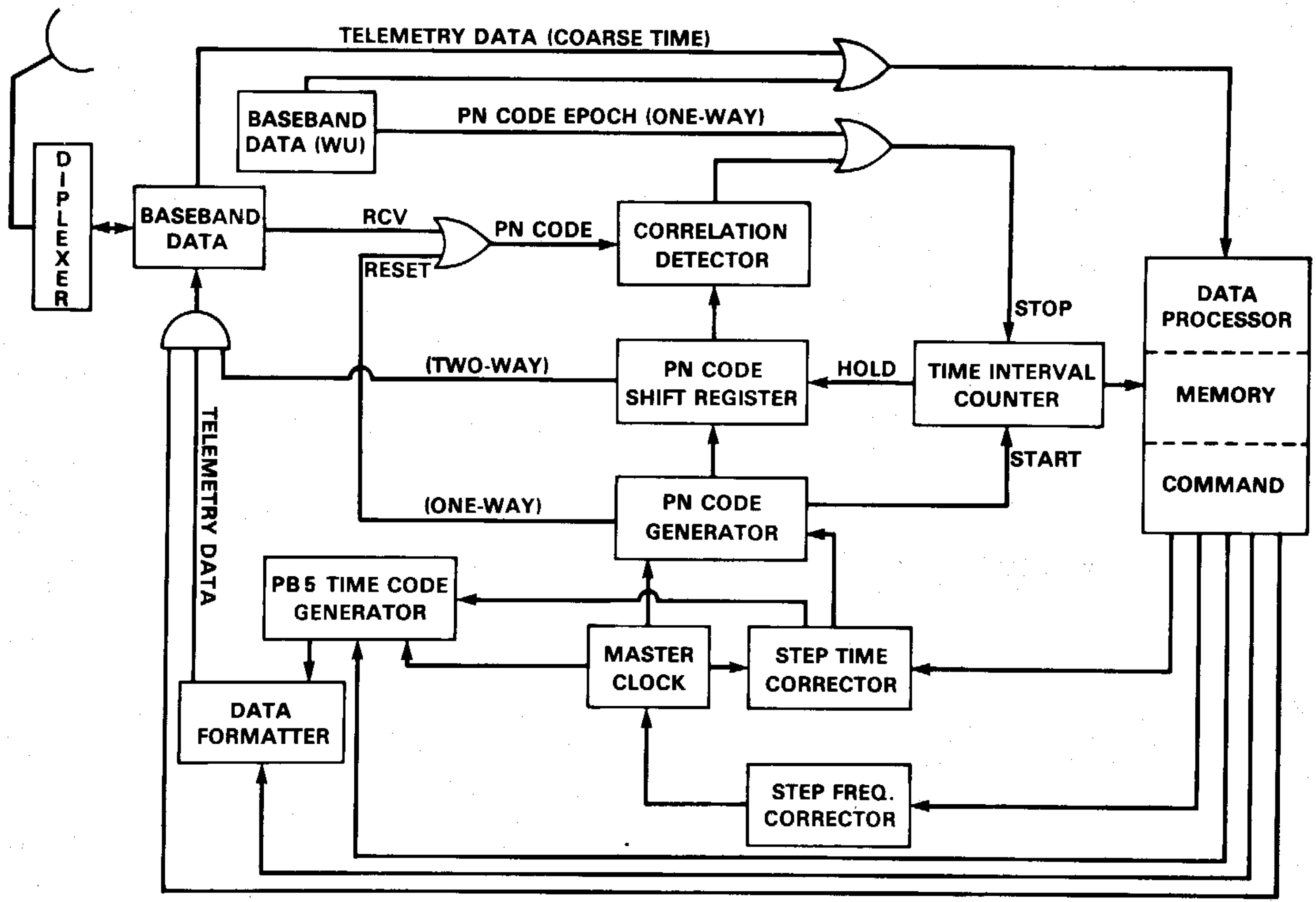


Figure 8. A Functional Block Diagram of the Ground Station Time Transfer Terminal

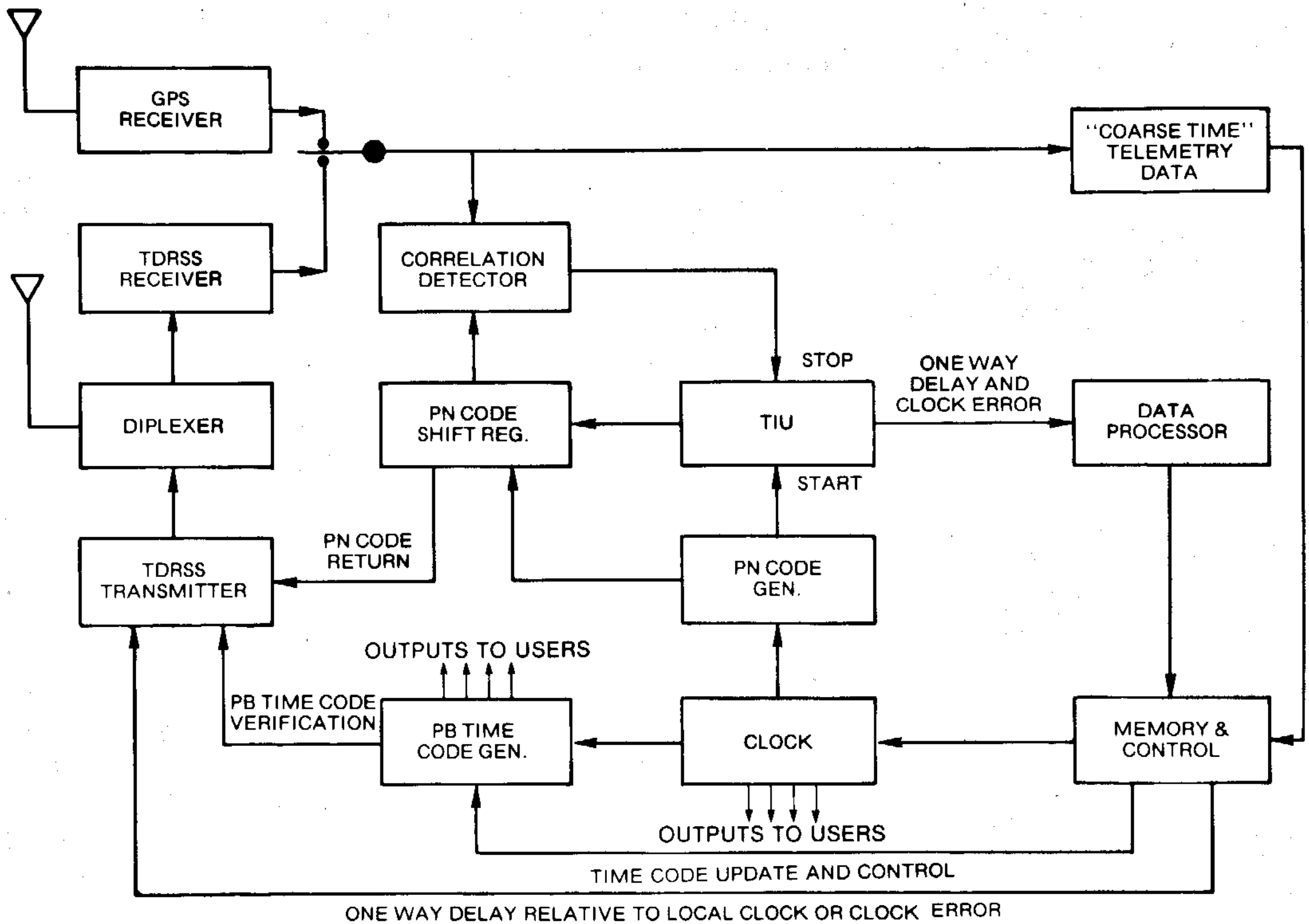


Figure 9. A Functional Block Diagram of Satellite Clock System

	MA	SSA	KSA
RF (MHz)			
FORWARD	2106.4	2025–2120	13775
RETURN	2287.5	2200–2300	15003
NO. OF RF LINKS			
FORWARD	2	4	4
RETURN	20	2	2
BANDWIDTH (MHz)			
BW (3db)	6	20	50
IF	NO	YES	YES
CHIP RATE			
FORWARD	$\frac{31F}{221 \times 96}$	$\frac{31F}{221 \times 96}$	$\frac{31F}{1469 \times 96}$
RETURN*	$\frac{31F_R}{240 \times 96}$	$\frac{31F_R}{240 \times 96}$	$\frac{31F_R}{1600 \times 96}$
DATA RATE	0.1–10kb/s	0.1–300kb/s	1kb/s–25Mb/s

* F_R IS THE DOPPLER COMPENSATED FREQUENCY RECEIVED BY THE USER.

Figure 10. Pertinent TDRSS Parameters

	COMMAND	RANGE
PN CODE LENGTH	$2^{10}-1$	$(2^{10}-1)2^8$
CHIP PERIOD (APPROX.)	332 ns	332 ns
RESOLUTION	3.3 ns	3.3 ns
AMBIGUITY PERIOD	333 μs	85 ms
ACQUISATION TIME (sec)		
MA	20	10
SSA	20	10
KSA	4	2

Figure 11. Pertinent TDRSS Parameters

1. TIME AMBIGUITY CONSIDERATION

$$R_2 = \sqrt{R_1^2 + R_e^2} = \sqrt{(6.6175^2 + 1)\, R_e^2}$$

$$= 6.6926\ R_e$$

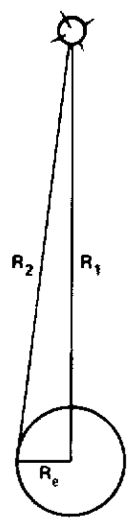
$$t_2 = \frac{R_2}{C} = 142.385\ \text{ms}$$

$$t_1 = \frac{R_1 - R_e}{C} = 119.514\ \text{ms}$$

$$t_2 - t_1 = 22.871\ \text{ms} \quad 23\ \text{ms}$$

TIME AMBIGUITY $\cdot 2(t_2 - t_1) = 46$ ms

R_e = 6378.175 km
C = 299792.5 km/s
$\cong$ 300 km/ms
= 300 m/μs
= 30 cm/ns



2. PREDICTABLE OR MEASURABLE DOPPLER CORRECTIONS DUE TO SATELLITE MOTION

	RANGE OF DOPPLER	DOPPLER CORRECTIONS**		
		RATE	0.5 SEC.	1/4 SEC.
ALL SAT.	6-8 km/s	20-27 μs/s	10-14 μs	5-7 μs
SYN. SAT.*	20-40 m/s	67-133 ns/s	34-67 ns	17-34 ns

* MAXIMUM VALUES
** UNCERTAINTY IS MUCH LESS THAN THE KNOWN CORRECTION

Figure 12. Ambiguity Consideration and Propagation Delay Corrections

3. TOTAL COMPOSITE ATMOSPHERIC CORRECTIONS* PROPAGATION DELAYS

FREQUENCY (GHz)	Δ t (ns)		
	ELECTION DENSITY		
	1 x 10^5	4 x 10^5	1.6 x 10^6
8	28	37	65
2	30	40	70

*BASED ON A TOTAL COMPOSITE ATMOSPHERE FROM THE SURFACE OF THE EARTH TO 5000 km ALTITUDE WITH A TYPICAL CONTRIBUTION FROM THE LOWER ATMOSPHERE MODELLED AFTER THAT ABOVE BARROW, ALASKA IN MAY. (SEE PROPAGATION DELAY IN THE ATMOSPHERE BY D.M. LeVINE GSFC DOCUMENT X-521-70-404, NOVEMBER 1970.)

Figure 13. Ambiguity Consideration and Propagation Delay Corrections

1. TDRSS ORBIT AND POSITION DATA CAN BE PROVIDED TO ONE-WAY USERS, BASED ON:

NO. OF GROUND STATIONS	7
POSITION ACCURACY OF GROUND STATIONS	200 m
RANGE ACCURACY	7 m
FREQ OF ORBIT DETERMINATION	ONCE PER DAY
ACCURACY OF ORBIT DETERMINATION	200 m
SATELLITE POSITION DATA OBTAINABLE	HOURS

2. BASED ON PREDICTED POSITION OF TDRS, USER CAN USE ONE-WAY TIME TRANSFER OPTION IF HE KNOWS HIS POSITION TO REMOVE THE RANGE DELAY.

Figure 14. One-Way Satellite Time Transfer Option and Accuracy

QUESTIONS AND ANSWERS

QUESTION:

The time codes which are used for the receivers, is this a standard code now or is it one you are proposing?

MR. CHI:

The time code is in the process of being reviewed by NASA and also by outside users. It is a power-binary time code, grouped-power-binary time code, which is under review and most likely will be in use for the spacecraft clock system. As I described before there is a truncated Julian date number with four digits and five digits for seconds of day and three digits for the milliseconds of seconds and so on. The total is 64 bits. That is an eight-bit, byte, R-entered code.

It is presented elsewhere so I did not want to repeat that code. If you are interested in it, I may have a copy of it and I would be happy to give it to you.

DR. KAHAN:

Can you compare this to transient rates on the GPS system? What is the difference in this case between the capabilities that this would provide and what one can get through their transient regular GPS receiver?

MR. CHI:

Obviously you can, provided of course you have the receiving terminal. For instance, I could suggest to have one of our terminals, which normally would be placed, for instance in Boulder, Colorado, that same type receiver can be placed into wherever time is wanted to be compared. For instance a monitoring station for our GPS if one wants to do that. You can receive the time from White Sands Station which will be synchronized to NBS.

Of course you can do it for all the monitoring stations that you wish. It is the same idea as for the primary time laboratories.

DR. WINKLER:

I think the comparison he asked for is the decision on that.

MR. CHI:

Oh, you use two-way propagation to measure the propagation delays. The method is to measure precisely the propagation delay time. Once you have the delay you can subtract the delay out. This could be to order the nanoseconds. It depends on the type of corrections one applies.