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STUDY OF A NAVIGATION AND TRAFFIC CONTROL TECHNIQUE EMPLOYING SATELLITES

(Final Report)

VOLUME V

• ADDENDUM

TRAFFIC CONTROL DATA LINKS

By Art Garabedian

OCTOBER 1968

Prepared under Contract No. NAS 12-539 by

TRW
SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH, CALIFORNIA 90278

Electronics Research Center

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1. INTRODUCTION AND SUMMARY

This report is an addendum to the four-volume interim report (Reference 1). Together the two reports constitute a final report for the study. The NAVSTAR satellites described in the interim report provide navigation information to system users. In addition, the satellites have some communications capability permitting the NAVSTAR ground-tracking network to relay satellite tracking data from remote sites to a central point. Because of the desirability of adding traffic control capability to the satellites, the communication capability has been expanded to provide for the relay of digital data between system users and a ground station in addition to relay of the satellite tracking data. The subject of this addendum is this expanded capability.

The added data links provide full duplex communications between system users and a ground station and will operate at L band. Therefore, the data links will be able to use the same antennas on the satellite and user proposed for navigation. The links will have the capacity to meet the estimated surveillance* requirements of an air traffic control system for the 1975 time period in the North Atlantic ocean area based on a four-satellite network and earth coverage satellite antennas. Four satellites are required to obtain a full three-dimensional (latitude, longitude, altitude) position fix.

Each aircraft in the traffic control system will periodically transmit the latest received NAVSTAR range (difference) data to a ground station. A ground-based computer will determine aircraft positions from the relayed data and the ground station can then relay to the aircraft for pilot display, instructions based on the position information as well as the actual position itself. This latter mode of operation corresponds to Configuration B of the NAVSTAR user equipment (Reference 1, Volume IV). As an upper bound on the data requirements, supersonic aircraft (the SST) are assumed to transmit data reports to the ground

*Defined here to mean position determination of aircraft by a traffic control ground station independent of pilot reports.

station every 20 seconds. All other aircraft (subsonic) are assumed to transmit data reports every 80 seconds. The peak North Atlantic aircraft population in 1975 is estimated to contain 20 supersonic and 170 subsonic aircraft.

An increase in the data rates beyond the surveillance requirements can be readily achieved by increasing the satellite antenna gain by narrowing the beamwidth from earth coverage to North Atlantic coverage. Data rates up to five times greater can be accommodated. The concomitant disadvantage is the limitation of NAVSTAR service to one area or a greater number of satellites to obtain worldwide coverage. The tradeoffs involved in increasing the satellite antenna gain need further study before a decision can be made as to the best approach.

A complete aeronautical service capability, including both digital and voice transmission, is not considered here for two reasons. First, it was desired to operate the links with the simple low-cost user navigation antenna rather than the heavy and costly steerable arrays required for voice and high data rate communications. Second, it was desired to maintain the present satellite size. Adding the digital data links for the surveillance function increases the satellite weight by 104 pounds at launch, but the satellite is still within the capability of the Intelsat III structure and a Thor-Delta launch vehicle. A full capability aeronautical satellite to meet the total requirements in the North Atlantic would require an Atlas/Agena class of launch vehicle.

In this addendum, the following information is presented. Section 2 describes the traffic control links and the attendant communications equipment required for the ground station, system users (assumed to be aircraft) and the satellites. Estimated data requirements for surveillance and link power budgets are also given. Section 3 discusses the satellite tracking data relay function, which has been modified because of the added traffic control links. This section replaces Section 4.9, Volume IV, of the interim report. Section 4 presents the impact on the satellite of adding the increased communications for traffic control. Finally, Section 5 estimates the user hardware costs to implement the traffic control communications, assuming a production run of 200 units.

2. TRAFFIC CONTROL DATA LINKS

The traffic control data links which have been added to the NAVSTAR system permit low rate digital data communications between appropriately equipped system users and ground stations via transponders on the satellites. Two RF links per satellite will be available, one link for ground-station-to-aircraft transmissions and the other for user-to-ground-station transmissions. Thus full duplex communications between users and the ground station are provided. Half-duplex communications (one link per satellite) reduces system efficiency by requiring the ground station and user transmissions to be synchronized. Guard times between transmissions to accommodate the propagation delay uncertainties between users and the satellites limit the utilization of such a half-duplex link. For these reasons full duplex communications are more desirable.

The data links will operate at L band so that the L-band despun navigation antenna on the satellite can also be used for the data relay. In addition, the low-gain user antenna recommended for navigation can also be used for the transmission and reception of the traffic control data. Therefore, no additional satellite or user antennas are required for the traffic control data function. The RF carriers will be frequency division multiplexed with the other L-band NAVSTAR carriers, i.e., the navigation (ranging) signal from the satellites to users and the satellite tracking data relayed by the satellite from remote ground tracking sites to a central station. The navigation signals are time division multiplexed between the satellites in the NAVSTAR network and are consequently at the same carrier frequency for each satellite. However, the traffic control data links will be available continuously from each satellite. Therefore, each satellite transponder will operate at a different set of frequencies, assigned in 500-kHz steps. Of course, in a worldwide system, satellites which can never be simultaneously in view can operate on the same frequencies. A typical frequency plan for a North Atlantic network of four satellites is shown in Table 1.

Table 1. Satellite Frequency Plan

Link	RF Frequency (MHz)			
Satellite	1	2	3	4
Transmitted Carriers				
ATC data to aircraft	1552.0	1551.5	1551.0	1550.5
ATC data to ground station	1547.0	1546.5	1546.0	1545.5
Satellite tracking data*	1542.0	1541.5	1541.0	1540.5
Navigation signal	1567.0	1567.0	1567.0	1567.0
Received Carriers				
ATC data from ground station	1660.0	1659.5	1659.0	1658.5
ATC data from aircraft	1655.0	1654.5	1654.0	1653.5
Satellite tracking data*	1650.0	1649.5	1649.0	1648.5

* All satellites need not be equipped for this function (see Section 3).

2.1 DATA REQUIREMENTS

The data rates for the links will have the capacity to handle the surveillance function of an air traffic control system for the North Atlantic ocean area in 1975. Data rates of 200 bits/sec from aircraft to ground station and 64 bits/sec from ground station to aircraft per satellite can be implemented without major change to the satellite size and can be handled by the satellite earth coverage and low gain user navigation antennas. An increase in data rates for expanded capacity would require either an increase in satellite or user antenna gain or a major change in satellite size to permit increased solar array power. Since it was desired to maintain the Intelsat III modification with a Thor-Delta launch vehicle for the NAVSTAR satellites and to maintain the simple nondirective user antenna, increased data rates by either of these methods was not considered. However, the data rates can be readily increased by narrowing the satellite antenna beam from earth coverage to North Atlantic coverage. Up to 7 db increase in satellite ERP can be obtained by this method providing up to a five times increase in data rate. The disadvantage is the narrower coverage in NAVSTAR service provided by each satellite.

The data requirements for surveillance will depend on the maximum number of aircraft in the North Atlantic at any one time. An average of the existing forecasts on traffic volume (Reference 2) indicate that the peak traffic will be approximately 190 aircraft, 170 subsonic, and 20 supersonic. The surveillance requirements are based on this estimate.

In order to bound the communication requirement, all 190 aircraft in the North Atlantic are assumed to be equipped to relay NAVSTAR data. Each aircraft transmits the data reports to the ground station either on request from the ground station or automatically in assigned time slots. The information and corresponding number of bits in each data report is shown in Table 2. The number of bits shown represent an upper bound

Table 2. Automatic Data Report, Upper Bound on Information Bits Required

Information	Decimal Digits	Binary Digits
Aircraft identification	6	20
NAVSTAR data		
Satellite identification	1/satellite	16*
Range	6/satellite	80*
Range rate	4/satellite	48*
Time	7	22
Altitude	4	14
Total		200 bits

* The number of bits represents data from four satellites.

on the requirements and allow determination of position to a resolution of 10 feet and velocity** to 1 ft/sec, considerably better than will be required for surveillance. However, since NAVSTAR can provide accuracies to this order of magnitude, the maximum resolution is assumed in order to

** Velocity information may not be required but is included since the system has this capability. Aircraft not equipped to measure velocity data from carrier doppler will not transmit this information.

place an upper bound on the data requirements. In the data report, the NAVSTAR range (difference) data from four satellites is included plus time to the nearest millisecond referenced to one satellite transmission time. Although altitude information is contained in the NAVSTAR data, altitude from the altimeter is also assumed to be transmitted.

The maximum data rate required for the surveillance of all 190 aircraft is estimated as follows: The 20 supersonic airacraft are assumed to transmit reports not more often than every 20 seconds and the 170 subsonic aircraft every 80 seconds. Therefore, the maximum data rate indicated is:

$$\frac{200 \text{ bits} \times 20 \text{ aircraft}}{20 \text{ sec}} + \frac{200 \text{ bits} \times 170 \text{ aircraft}}{80 \text{ sec}}$$

for a total of 625 bits/sec. To accommodate frame sync and guard time between aircraft transmissions, a 20 per cent greater data rate is assumed. Therefore, the maximum data rate from aircraft to the ground station for surveillance will be approximately 750 bits/sec. Since each satellite can relay 200 bits/sec, a four-satellite network can handle 800 bits/sec and maximum surveillance requirements can be met by this network.

The data rate from the ground station to aircraft is derived as follows: If the ground station requests surveillance information from aircraft on a roll call basis by transmitting aircraft identifications sequentially, the necessary data rate is:

$$\frac{20 \text{ bits} \times 20 \text{ aircraft}}{20 \text{ sec}} + \frac{20 \text{ bits} \times 170 \text{ aircraft}}{80 \text{ sec}} = 63 \text{ bits/sec}$$

If the aircraft report automatically in assigned time slots, these ground station transmissions can of course be eliminated.

An additional capability of 147 bits/sec (after providing 20 per cent for sync, guard time) is available on the ground-station-to-aircraft link based on the four-satellite network and 64 bits/sec relay capacity per satellite. This additional data capability can be used to send users traffic control instructions as required and statements of position data for straying aircraft and for aircraft which do not contain NAVSTAR navigation computers.

The surveillance sampling rates upon which the preceding data rates were based are the results of studies by TRW under NASA/ERC contract NAS 12-595 for which the final report has not been prepared as of this writing. If lower sampling rates prove feasible, the extra data rate capacity can be used for added traffic control functions or for system growth. Higher sampling rates are felt to be unlikely.

2.2 SATELLITE ACCESS METHODS

Access to a particular satellite would be assigned to users on a geographic basis. For example, in the North Atlantic network, the area would be divided into four zones. Each of the four satellites would be assigned a particular zone on the basis of best orbit coverage. All users in a given zone would tune their transceivers to the pair of frequencies assigned to the satellite covering that zone. Upon entering a new zone, users would simply switch their frequencies to the next satellite.

Access to a satellite by all users in a given zone can be solved by two different approaches. In the first approach, users transmit data only upon receipt of ground station requests (the roll-call method). The ground station can address a group of users in any sequence and frequency of contact desired. In the second approach, each user is assigned a time slot. The time information supplied as part of the navigation signal transmissions can be used for the time synchronization required between users. Assignments of time slots to users as they enter new zones can be made by ground station transmissions.

Of the two approaches the first appears to be the more attractive since it allows for more flexible operation of the traffic control network. Another possibility would use a combination of the two approaches. Users would ordinarily broadcast in their assigned time slots. However, the ground station could override this system by sending appropriate instructions to all users. The instructions could make available more time slots (more frequent ground station contact) to certain users and fewer time slots to other users or could change the mode of operation from time slots to ground station requests.

2.3 MODULATION-DEMODULATION TECHNIQUES

The modulation-demodulation techniques for the traffic control function have been designed to provide minimum complexity of user equipment within the constraints of limited satellite RF power. Many digital techniques were considered using both coherent and noncoherent detection. Coherent detection while more efficient in the use of satellite RF power is unattractive from the standpoint of requiring the receiver to acquire the phase of the arriving carrier. The acquisition takes a portion of the transmission time thus reducing data transmission capacity. However, at L band, doppler shift (especially with the supersonic aircraft) and system oscillator frequency uncertainties become significant in that arriving signals at the user, satellite, and ground station have relatively large frequency uncertainties (12 to 20 kHz) compared to the modulation bandwidths of the transmitted data rates. Consequently, noncoherent detection will suffer significant degradation in performance since the receiver predetection bandwidth must be made much larger than the modulation bandwidth unless the receiver employs some form of automatic frequency control. Because of the large uncertainty in frequency, a wideband AFC loop such as used in home broadcast FM receivers will not work well because of the thresholding effect in the loop discriminator. Therefore, a narrowband tracking loop (either a frequency or phase lock loop) is required which will acquire and track a carrier or pilot tone.

The ground station receiver will not require automatic frequency control since it can compensate for receiver performance degradation by increased antenna gain. In addition, since the ground station receives signals in rapid sequence from many different users, acquisition of a pilot tone for each received signal would reduce the time available for data reception.

Users present a different case. Degradation in receiver performance cannot be tolerated since the user antenna gain is limited to low values. Therefore, the user receiver will require a narrowband tracking loop to remove the frequency uncertainty in the arriving signal. Consequently the ground station will continuously emit a carrier or pilot tone and users will acquire the carrier upon entering a traffic control zone and stay locked to this carrier while remaining in the zone.

In view of these considerations, the following modulation techniques are chosen for the data transmissions. Users transmit frequency shift keyed data (FSK) with two L-band frequencies spaced 80 kHz apart and keyed at a rate of 200 times per second (200 bits/sec). The ground station demodulator detects the tones with two wideband filters and envelope detectors centered on the nominal tone frequencies. The degradation in signal-to-noise ratio with the wideband filters can be tolerated because of the large ground antenna gain.

The ground station transmits its data by FSK of two audio tones (at 64 bits/sec) which phase modulate the L-band carrier. The modulation index will be small enough to provide a carrier component for the user to acquire and track by a phase lock loop. The user receiver maintains lock to the carrier, thus removing the arriving frequency uncertainty. The audio tones recovered by the phase lock loop are detected by filters to recover the data. However, the tone filters can now be narrowband resulting in near optimum detection for FSK. The optimum filters for FSK are bandpass integrate and dump filters (the matched filter). Ordinary bandpass filters, such as RLC filters, with bandwidths approximating the bit rate are near optimum in performance (about 1 to 2 db degradation from optimum) and much simpler to implement. See Reference 3.

2.3.1 User-to-Ground Station Link

A simplified block diagram of the ground station demodulator is shown in Figure 1. The demodulator contains a pair of bandpass filters. One filter is tuned to one of the data tones (the "mark" filter) and the other is tuned to the other data tone (the "space" filter). The signals out of the two filters are envelope detected and a mark-space decision on the data is made every bit time according to which envelope detector output voltage is larger. Before a decision is made, the outputs from the two envelope detectors are differenced to form a plus-minus level signal (contaminated by noise) and filtered by the optimum filter for this signal (the integrate and dump filter). The integration period extends over one

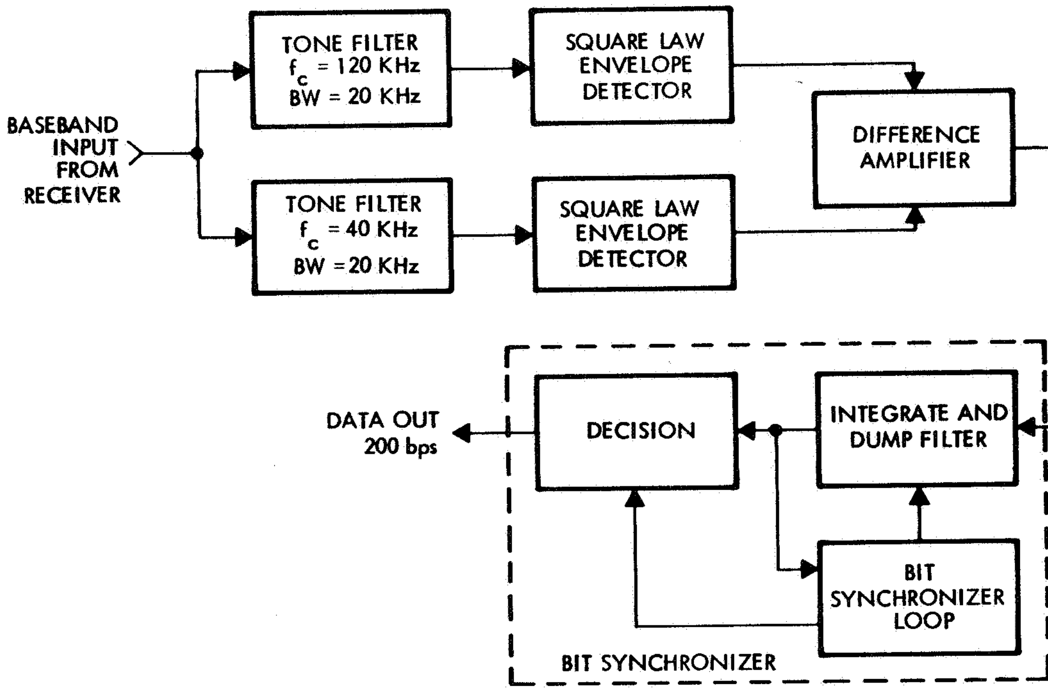

Figure 1. Ground Station Data Demodulator

bit time, at the end of which the filter output polarity is sampled by the decision circuit and then dumped to prepare for the next bit. The output of the decision circuit constitutes the binary traffic control data received by the ground station. The decision-sampling and integrate-and-dump operations require bit synchronization, which is provided by the bit sync loop operating on the bit transitions. It will be necessary for each message to contain some bit transitions at the start for the purpose of synchronizing the loop and for the message to contain sufficient data transitions to maintain synchronization.

The data demodulator would be near optimum in performance if the bandpass filters had noise bandwidths about equal to the data rate. Unfortunately, the frequency uncertainty in the RF link is much larger than the transmitted data rate and the filter bandwidths must be expanded to accommodate the total expected frequency uncertainty. The total uncertainty will depend on the system oscillator stabilities and the doppler shift resulting from the relative velocity of the satellite and the transmitting user. The satellite will make a negligible contribution since at synchronous altitude doppler is very small; the frequency translation error in the transponder can be made negligible by proper design. A maximum frequency uncertainty of about 17 kHz is estimated based on the following assumptions:

1) The maximum user velocity will be 3000 ft/sec corresponding to the SST aircraft. This corresponds to about ±3 ppm maximum doppler shift of the carrier frequency.

2) The user transmitter contains an oscillator with a stability of at least ±2 ppm.

3) The ground station local oscillator in the receiver will have a stability of better than ±0.1 ppm.

4) The satellite transponder introduces negligible error in frequency translation and has near zero doppler effect compared to the maximum user velocity of 3000 ft/sec.

Therefore, assuming worst case linear summation of the individual frequency errors, the maximum frequency uncertainty for the link is ±5.1 ppm. At the maximum carrier frequency of 1660 MHz, this value corresponds to ±8.5 or 17 kHz total uncertainty in carrier frequency.

Since the ground station receiver is noncoherent and simply heterodynes the carrier frequency to video baseband, this frequency uncertainty also appears at the input to the demodulator. Without automatic frequency control, the FSK filters thus have to have passbands at least 17 kHz wide. This passband contrasts with the bandwidth necessary to pass the FSK modulation of only about 200 Hz. Tone filter noise bandwidths of 20 kHz are used to accommodate the 17 kHz uncertainty and the performance degradation with respect to optimum filtering is accepted. The two FSK tones transmitted by the user are spaced ±40 kHz about the nominal L-band carrier frequency assigned to the link. Thus the tones are spaced 80 kHz apart, which simplifies the filtering requirements in the ground station demodulator. The tone filters in the demodulator are centered at 40 and 120 kHz, as illustrated in Figure 1.

Error rate as a function of the signal-to-noise ratio in each tone filter has been calculated by Glenn (Reference 4) for different values of the ratio of the filter noise bandwidth to the data rate. This ratio is 100 in the present case (20 kHz and 200 bits/sec). For a desired bit error rate of 10^{-5}, the required signal-to-noise ratio in the 20-kHz noise bandwidth is, according to Glenn, about -1.0 db. The optimum noncoherent FSK demodulator has a probability of a bit error (Reference 5) of

$$P_e = \frac{1}{2} \exp \left[- \frac{E}{2N_o} \right]$$

where E/N_o = energy per bit-to-noise spectral density. For P_e of 10^{-5}, E/N_o is 13.4 db for optimum demodulation and 19.0 db for the wideband filters. Therefore the degradation in performance with the wideband filters is slightly less than 6.0 db.

Other noncoherent techniques plus differentially coherent PSK were also considered for this link but each was ruled out for reasons of performance or ease of implementation or both. The noncoherent FSK modulation-demodulation technique described here appears to be the best choice for the L-band traffic control data links from system users to the ground station via relay from the NAVSTAR satellites.

2.3.2 Ground-Station-to-User Link

As discussed previously, the users in this link will have phase lock receivers which track the carrier component of the ground station transmissions. Either a frequency or phase tracking loop can be used in this application. There appears to be no particular advantage to either technique; both have about the same performance and both require a carrier signal to acquire and track. The main difference is in the modulation form and implementation. Without the benefit of further study on the tradeoffs involved between the two schemes, a phase lock loop has been chosen on the basis of greater experience with this type of receiver.

Carrier tracking is necessary to remove the large uncertainty in the frequency of the received carrier. The magnitude of this uncertainty is about the same as for the user-to-ground station link (17 kHz) since similar assumptions on oscillator stabilities and doppler shifts apply. Therefore, if the frequency uncertainty is not removed, the ratio of the required filter detection bandwidths (20 kHz) to the data rate for this link (64 bits/sec) is 312.5. From Glenn (Reference 4), the degradation from optimum detection is calculated to be about 9 db. This is clearly intolerable for the limited gain available in the link.

The carrier can be acquired manually. To aid in acquisition the carrier loop has two loop bandwidths selectable by a switch with acquisition occurring in the wideband position (150 Hz, two-sided). After acquisition, the loop is switched to the narrowband position (50 Hz) to improve the loop signal-to-noise ratio. A higher S/N in the loop during tracking is desirable to prevent carrier noise jitter in the loop from degrading the data demodulator performance.

The data modulation is contained in two audio tones ("mark" and "space") which phase modulate the carrier. The output of the phase-lock receiver contains the two keyed tones, only one of which is present at any given time (FSK). Consequently, the data demodulator following the phase-lock receiver (see Figure 2) has the same form as the noncoherent FSK demodulator in the ground station. The important difference is that near-optimum filtering of the tones is possible since the carrier loop has removed the frequency uncertainty in the L-band carrier.

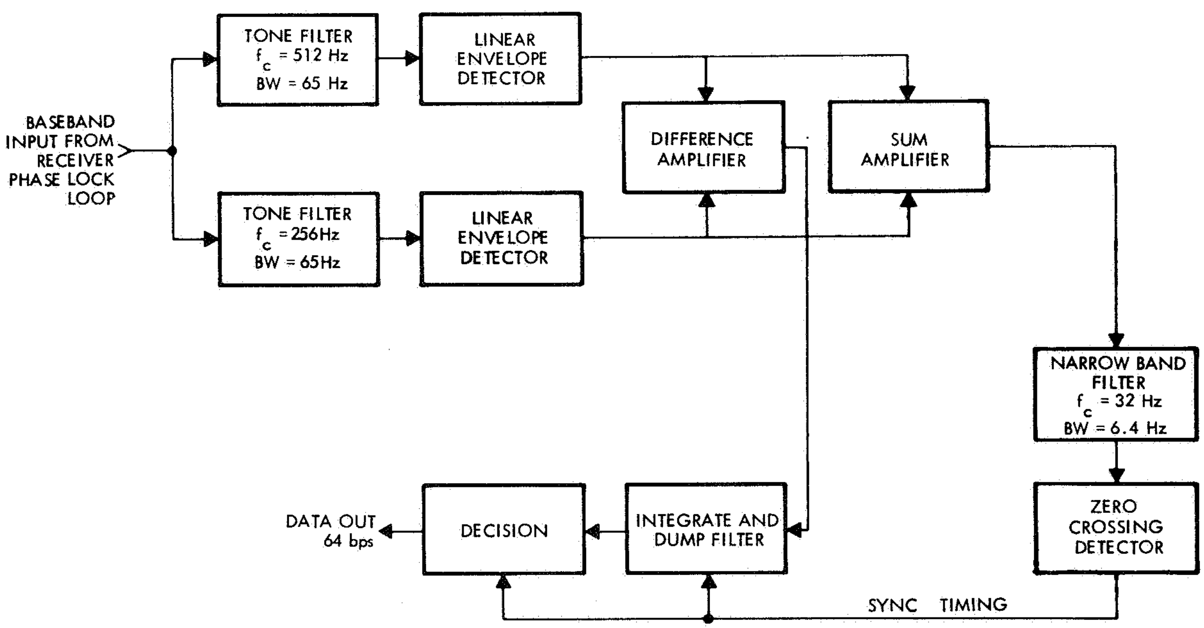

Figure 2. User's Data Demodulator

The bandwidth of the "mark" and "space" filters is just wide enough to pass the modulated tones, or about 65 Hz. Tone frequencies of 256 and 512 Hz were selected to ease the narrowband filter designs required. If these frequencies turn out to be too close to the carrier, causing difficulty in carrier acquisition (locking on the tone sidebands), the tones can be transmitted at higher frequencies and then heterodyned to the selected frequencies prior to filtering.

Besides narrowband filtering of the tones, the other major difference from the ground station demodulator is the method by which bit sync is derived. In the ground station, bit sync is obtained from a bit sync loop operating on the data transitions. In order to simplify bit sync in the user demodulator, the ground station transmits bit sync information with the data. Bit sync is transmitted by amplitude modulating the combined FSK audio tone signal with a sinusoidal tone at 32 Hz (half the bit rate). The tone filters are widened slightly to accommodate this additional modulation. To recover the sync, the outputs of the envelope detectors (each output containing one-half cycle of the sync tone) are summed and filtered by a narrowband filter centered at 32 Hz. A zero crossing detector provides the sync timing. This technique has been employed successfully in the Air Force's SGLS command decoder.

The use of ordinary bandpass filters, such as an RLC filter in place of matched filters, will degrade performance about 1.0 to 2.0 db (see Reference 3). In addition, the bit sync amplitude modulation requires an increase in signal power by the factor $(1 + m^2)/2$, where m is the AM index of the sync tone. Reference 6 shows that $m = 0.5$ is sufficient to provide good bit sync timing accuracy (less than 3 per cent of the bit time) providing the bit sync filter has a bandwidth of about one-tenth the data rate, or 6.4 Hz. Thus bit sync requires an increase in power of only 0.5 db. The required ratio of total energy per bit-to-noise spectral density or equivalently the signal-to-noise ratio in a bandwidth equal to the bit rate will therefore be 15 to 16 db for $P_e = 10^{-5}$.

Since some power must remain in the carrier for the acquisition and tracking function, the modulation index of the data tones phase modulating the carrier must be chosen to optimize the division of power between the carrier and the tones. The optimum division of power has been shown (Reference 6) to be

$$\frac{J_1^2(\beta)}{J_o^2(\beta)} = \frac{1}{2}\left(\frac{P_d}{P_c}\right)$$

where β = carrier modulation index of tones (peak radians)

P_d/P_c = ratio of power required in data tones to power required in carrier

The value for the power ratio can be computed from the following requirements. The data tones require 16 db signal-to-noise ratio in a 64-Hz bandwidth, and the carrier loop requires 6 db signal-to-noise ratio in a 150-Hz bandwidth for acquisition. Straightforward calculation gives a value of 4.27 for P_d/P_c. The optimum modulation index is thus 1.7 radians.* The power required in the carrier results in a 1.8 db loss in the data power $[2J_1^2(\beta)]$. This loss contrasts with a 9-db loss if frequency uncertainty were not removed by carrier tracking.

2.4 COMMUNICATIONS EQUIPMENT

The communications equipment required for the traffic control data relay between system users and a ground station are described to the block diagram level in this section, including the ground station, users, and the satellite transponder. Data processing equipment such as data storage and display of the traffic control data is not discussed but simply shown as a data input-output black box.

2.4.1 Ground Station

The main elements of the ground station transceiver (Figure 3) are a modulator and 100-watt amplifier for transmitting traffic control data to users plus a double conversion receiver and FSK demodulator for receiving traffic control data from users. A 26-db gain L-band antenna (5-foot dish) and associated diplexer are used for transmission and reception of the data signals. The equipment is for use with one NAVSTAR

*Carrier tracking requires slightly less power in the carrier than acquisition (10 db signal-to-noise ratio in a 50-Hz loop noise bandwidth) and if tracking only was considered the optimum modulation index would be 1.76 radians.

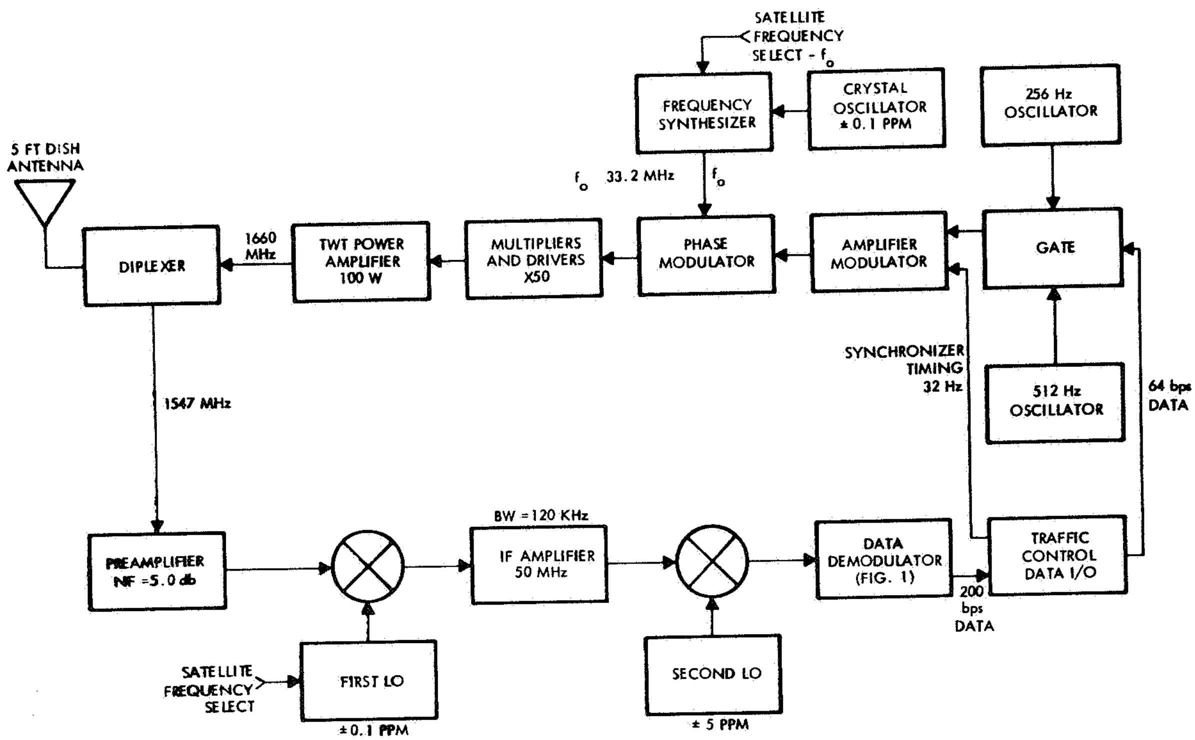

Figure 3. Ground Station Traffic Control Data Transceiver

satellite or traffic control zone. Duplicate equipment would be provided for each zone assigned to a station.

The 5-foot antenna has a beamwidth at the 3-db points of about 8 degrees. Therefore, azimuth tracking of the satellites will probably not be necessary and elevation tracking can be crude. In any case, the 5-foot antennas are low cost and provide no problems for the simple tracking required.

The transmitter portion contains two data tone oscillators at 256 and 512 Hz which are selected for transmission through an analog gate by the binary data stream to be transmitted. The tones are obtained by a tuning fork reference or by dividing down a high frequency crystal oscillator. The gate output, consisting of the FSK data, is 50 per cent amplitude modulated by a 32-Hz sinusoidal timing waveform representing the sync information for the 64 bits/sec data stream. The composite signal phase modulates the output of a frequency synthesizer driven by a stable crystal oscillator (±0.1 ppm). The phase-modulated signal is multiplied to L band and amplified to 100 watts output power by a TWT amplifier. The amplifier output is fed to the diplexer and antenna for transmission to a satellite. The ground station can select its transmitter frequency to work with a particular satellite by selecting the proper frequency output from the synthesizer.

The receiving portion consists of a double conversion superheterodyne receiver preceded by an L-band transistor preamplifier with 5-db noise figure. The output from the second converter contains the two data tones at frequencies of 40 and 120 kHz and forms the input to the FSK demodulator (see Figure 1). The local oscillator frequencies can be derived from the frequency synthesizer in the transmitter or can be separate units. It is important for the first local oscillator to have a stability of at least ±0.1 ppm, although the second local oscillator can have a stability of ±5 ppm since it does not contribute significantly to the frequency error in the tones. The IF following the first converter must have a bandwidth large enough to pass the two data tones. Since the tones are 80-kHz apart and are modulated with narrowband information (200 bits/sec data) an IF bandwidth of 100 kHz should be adequate. The receiver can be tuned to any of the satellite frequencies by selection of the first local oscillator frequency.

2.4.2 System Users

The main elements of the transceiver required by users of the traffic control system are a modulator and 300-watt amplifier for transmitting traffic control data to the ground station plus a phase-lock receiver and demodulator for receiving traffic control data from the ground station. See Figure 4. The antenna is the same one used for reception of the navigation signals from the satellites. Its coverage extends over the upper hemisphere so that tracking of the satellites is not required. For a discussion of the navigation antennas see Reference 1, Volume III.

The transmitter portion contains a crystal oscillator with ±2 ppm stability. A frequency synthesizer generates the two data tones spaced 80 kHz apart which are selected for transmission through an analog gate by the binary data stream to be transmitted. The gate output is multiplied to L band by a multiplier chain and amplified to 300 watts output power. The output of the power amplifier is fed to the diplexer and antenna for transmission to a satellite. The transmitting frequency to

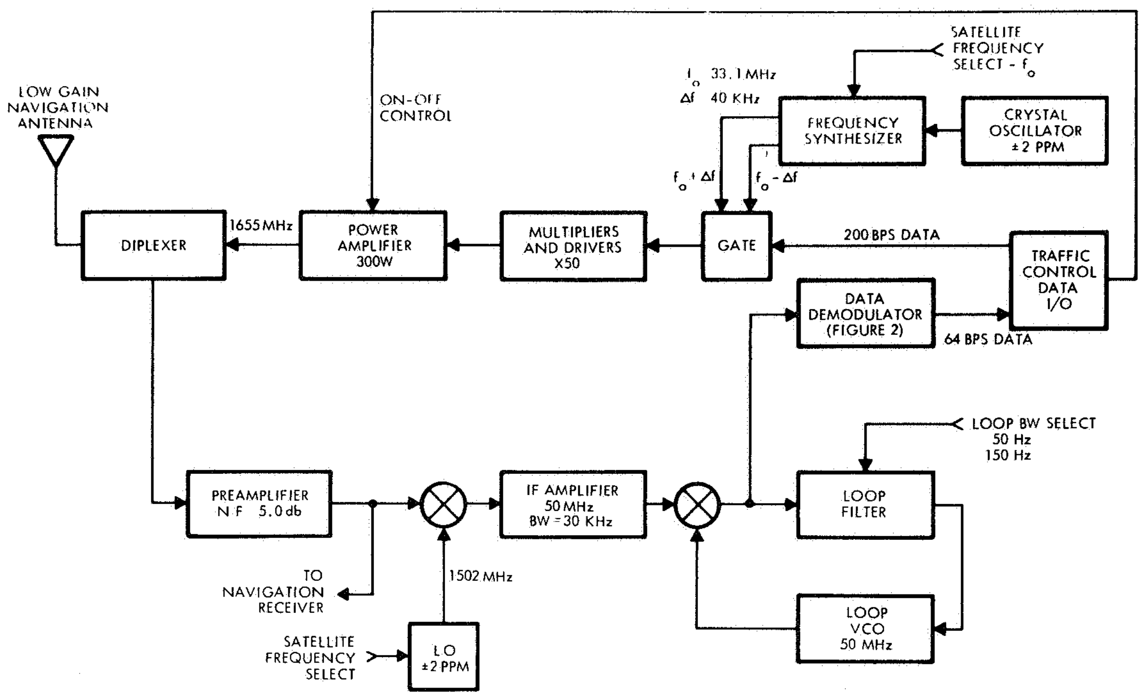

Figure 4. User Traffic Control Data Transceiver

operate with a particular satellite is selected by choosing the proper pair of 80-kHz spaced data tone frequencies generated by the frequency synthesizer.

The receiving portion consists of a simple phase lock loop receiver. The L-band preamplifier preceding the receiver can be the same one used with the navigation receiver. Since the traffic control and navigation links are close in frequency (see Table 1), the bandwidth requirements on the preamplifier to pass the two RF signals will not be excessive. The preamplifier output goes to the first mixer, which is driven by a local oscillator. The local oscillator frequency can be derived from either the crystal oscillator in the transmitter or from a separate oscillator. The receiver can be tuned to any of the satellite frequencies by selection of the local oscillator frequency. The 50-MHz IF will have a bandwidth of 30 kHz, more than enough to pass the total frequency uncertainty (20 kHz) of the received L-band carrier plus the narrowband data modulation (about 1 kHz). The IF output goes to the carrier phase lock loop, where the frequency uncertainty is removed. The loop has two manually selected noise bandwidths of 50 and 150 Hz for acquisition and tracking. The output from the loop phase detector contains the data tones of 256 and 512 Hz plus the AM sync information.

2.4.3 Satellite Transponder

The satellite transponder used to relay the traffic control data between users and a ground station is shown in Figure 5. Tentative gain distributions of each stage are shown plus the DC power input required and the estimated size and weight of the unit. In addition to relaying the traffic control data the transponder is configured to handle the relay of the satellite tracking data from remote tracking stations to a central station, discussed further in Section 3. The transponder is a frequency translating repeater with individual IF channels for each received carrier. The three IF channels will handle simultaneously three received L-band carriers, the two traffic control data carriers from the ground station and user (full duplex operation), and the satellite tracking data carrier from the remote tracking sites.

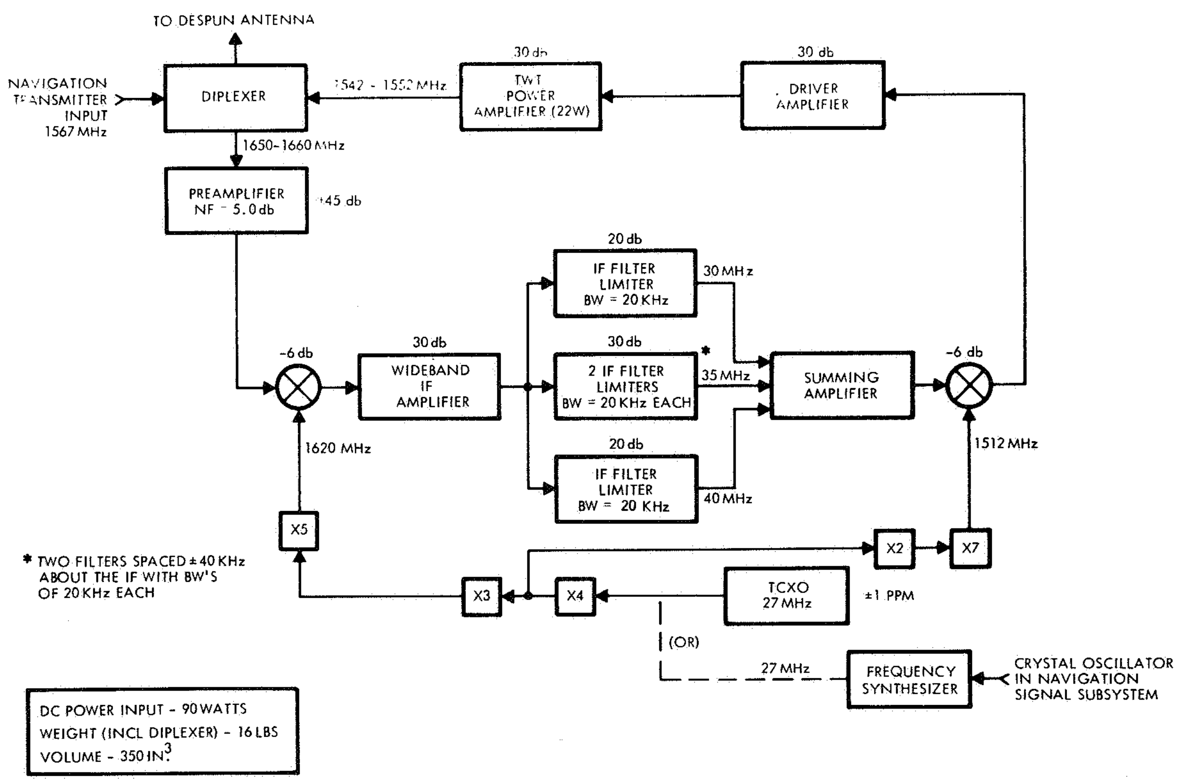

Figure 5. Satellite Transponder

The L-band despun antenna for the navigation signal transmissions is also used with the transponder. The output of the diplexer goes to a multistage preamplifier with 5.0-db noise figure and 45-db gain. The down converter (first mixer) converts the received signals to the center frequencies of the three channel IF amplifiers (30 to 40 MHz). Each IF channel has a maximum output determined by limiting action. The three IF outputs are linearly added by the summing amplifier. The relative output levels of the three signals from the summing amplifier are adjusted to obtain the proper division of the total output power from the TWT for the three transmitted carriers. Limiting in the IF channels is required to prevent an unusually strong received signal from capturing an improper share of the output power. Since each channel is separately limited, intermodulation between the carriers is not a problem.

The summing amplifier output is converted to L band. The driver and TWT amplifier increase the power to the required level for transmission of the three received carriers. The total output power from the TWT is 22 watts, 20 watts for the traffic control carrier to users, 1 watt for the traffic control carrier to the ground station, and 1 watt for the satellite tracking data carrier.

The local oscillator frequencies for the converters can be synthesized from either the stable crystal oscillator used in the navigation signal subsystem or from a separate stable crystal oscillator (±1 ppm). The two conversion frequencies are separated by 108 MHz so that received carriers are translated down in frequency by 108 MHz before retransmission. The translations are implemented so that any frequency error in the crystal oscillator is cancelled out except the portion corresponding to the 108-MHz translation. If a separate crystal oscillator with stability of ±1 ppm is used, the corresponding transponder frequency translation error is only ±108 Hz. Therefore, the transponder makes virtually no contribution to the frequency uncertainty in the carriers arriving at the ground station and users. The fixed spread of 108 MHz between received and transmitted carriers is used to ease the diplexer requirements. Consequently, spectrum at both edges of the L-band region is required to implement the total system.

The bandwidths for the IF channels must be wide enough to accommodate the modulation bandwidth plus the expected frequency uncertainty in the carriers arriving at the satellite. For the traffic control ground station and remote site tracking carriers the following assumptions can be made:

1) The satellite doppler motion is small (less than 400 ft/sec).

2) The transponder down converter local oscillator frequency has a stability of at least ±1 ppm.

3) The ground transmitters have carrier stabilities of at least ±0.1 ppm.

4) The modulation bandwidth of the carriers are about 1 kHz for the traffic control ground stations and 4 kHz for the remote site tracking stations.

Consequently, the IF bandwidths for these two carriers would have to be at least 4.5 and 7.5 kHz, respectively. However, to ease the IF filter design, a noise bandwidth of 20 kHz has been assumed for both of these channels.

For user carriers the first two assumptions above also apply, together with the following:

1) The user will have a maximum doppler velocity of 3000 ft/sec (assuming an SST aircraft).

2) The user transmitter has a stability of ±2 ppm.

3) The modulation consists of two narrowband signals (less than 1 kHz apart) centered on the two L-band data tones spaced 80 kHz apart.

Consequently, the IF bandwidth required is 80 kHz plus 20 kHz uncertainty or 100 kHz total. However, 100 kHz would result in a poor IF signal-to-noise ratio. Therefore, the IF is split into two parts. Each part is centered on one of the data tones and has a noise bandwidth of 20 kHz. The total noise bandwidth is then 40 instead of 100 kHz.

The IF's of 30, 35, and 40 kHz correspond to a particular set of frequency assignments for a satellite (see Table 1). To change frequencies for other satellites, the transponder IF's are tuned to a different set of frequencies in steps of 500 kHz. For example, the next satellite transponder would have IF frequencies of 29.5, 34.5, and 39.5 MHz. If all satellite transponders do not require the full communications capability, it would be a simple matter to remove one of the IF's.

2.5 LINK POWER BUDGETS

Power budgets for the traffic control links to and from the satellites are given in this section. The space loss for each link assumes synchronous altitude and maximum slant range to the satellites. For a total satellite RF power of 21 watts devoted to the traffic control (20 watts to users and 1 watt to the ground station) and the earth coverage antenna (+29.2 dbw EIRP), each satellite is capable of transmitting 200 bits/sec of data to the ground station and 64 bits/sec of data to users. These rates are adequate, based on a four-satellite network, to handle the surveillance requirements for a North Atlantic air traffic control system in the 1975 era. Other data rates with different antenna gains are discussed at the end of the section.

2.5.1 Ground-Station-to-Satellite Link

The power budget for the uplink, shown in Table 3, provides a signal-to-noise ratio in the transponder IF of 28 db. Although no particular value is required for this signal-to-noise ratio, as it decreases in value the downlink degrades as the result of the effects of uplink noise. Degradation of the downlink by the uplink noise occurs from two effects. First, the noise takes a portion of the total available satellite transmitted power, thus reducing the effective transmitter power for the signal. Second, the uplink noise adds to the downlink noise increasing the overall noise spectral density in the downlink receiver. The magnitudes of these two effects are given by

$$\alpha = 10 \log \left[1 + (N/S)_{IF} \right]$$

$$\gamma = 10 \log \left[1 + \frac{S_d \, \Phi_u}{S_u \, \Phi_d} \right]$$

where α and γ are, respectively, the reduction in satellite transmitter power for the signal and the increase in downlink receiver noise spectral density expressed in decibels and where

$(N/S)_{IF}$ = transponder IF noise-to-signal power ratio

S_u, S_d = received signal levels on uplink and downlinks

Φ_u, Φ_d = uplink and downlink receiver noise spectral densities

The degradation of the downlink (satellite-to-users) from noise on the uplink will be negligible due to the strong received signal and IF signal-to-noise ratio in the transponder. Therefore, a 100-watt ground station transmitter and 26-db gain antenna (46 dbw EIRP) are more than adequate for this link.

Table 3. Ground Station-to-Satellite RF Link Power Budget (f_c = 1660 MHz)

Parameter	Value
Ground station transmitter power (100 watts)	+50.0 dbm
Circuit losses (diplexer, etc.)	-1.5 db
Antenna gain (5-ft dish)	+26.5 db
Space loss (22,000 nmi range)	-189.0 db
Satellite antenna gain (earth coverage)	+16.0 db
Circuit losses (diplexer, etc.)	-1.0 db
Net transmission loss	149.0 db
Received signal power	-99.0 dbm
Receiver noise spectral density (5.0 db N.F.)	-169.0 dbm/Hz
IF noise bandwidth (20 kHz)	43.0 db
IF noise power	-126.0 dbm
IF signal-to-noise ratio)	+28.0 db

2.5.2 Satellite-to-User Link

The power budget for the satellite-user link is shown in Table 4. To relay the 64 bits/sec from the ground station 20 watts are needed. This transmitter power is sufficient to permit, with 5 to 6 db signal margin acquisition and tracking of the carrier by the two loop bandwidths in the user receiver and detection of the data with a bit error probability of

Table 4. Satellite-to-User RF Link Power Budget (f_c = 1552 MHz)

Parameter	Value	
Satellite transmitter power (20 watts)	+43.0 dbm	
Power loss to uplink noise	0 db	
Circuit losses (diplexer, etc.)	1.0 db	
Antenna gain (earth coverage)	16.0 db	
Space loss (22,000 nmi range)	188.4 db	
User antenna gain (three-element slot dipole)	3.0 db	
Circuit losses (diplexer, etc.)	1.5 db	
Net transmission loss	171.9 db	
Received signal power	-128.9 dbm	
Receiver noise spectral density (5.0 db N.F.)	-170.0 dbm/Hz	
Uplink noise contribution	0 db	
Carrier Acquisition and Tracking		
Modulation loss (mod. index = 1.7 radians)	8.0 db	
Received carrier power	-136.9 dbm	
	Acquisition	Tracking
Carrier loop noise bandwidth	(150 Hz) 21.8 db	(50 Hz) 17.0 db
Carrier loop noise power	-148.2 dbm	-153.0 db
Carrier loop SNR	11.3 db	16.1 db
Required loop SNR	6.0 db	10.0 db
Margin	5.3 db	6.1 db
Data Tones Detection (256 and 512 Hz)		
Modulation loss (mod. index = 1.6 radians)	1.8 db	
Received data power	-130.7 dbm	
Data noise bandwidth (64 bits/sec)	18.0 db	
Data noise power	-152.0 dbm	
Data SNR	21.3 db	
Required SNR ($P_e = 10^{-5}$, AM sync tone)	16.0 db	
Margin	5.3 db	

10^{-5}. The required data signal-to-noise ratio (in a 64-Hz bandwidth) of 16.0 db was derived in Section 2.3.2. An upper hemispherical coverage antenna with 3-db gain is assumed for reception of the traffic control data. This antenna can be the three-element slot dipole antenna used for navigation and described in Reference 1, Volume III. Use of the 0-db gain turnstile antenna (also described in Volume III) would require a reduction in data rate to 32 bits/sec.

2.5.3 Users-to-Satellite Link

The power budget for the user-satellite link is shown in Table 5. The user transmitter power of 300 watts and the 3-db gain slot dipole antenna result in a satellite transponder IF signal-to-noise ratio of 8.3 db in each tone filter. Thus this uplink is considerably weaker than the uplink from the ground station, for which the IF signal-to-noise ratio

Table 5. User-to-Satellite RF Link Power Budget (f_c = 1665 MHz)

Parameter	Value
User transmitter power (300 watts)	+54.8 dbm
Circuit losses (diplexer, etc.)	1.5 db
Antenna gain (slot dipole)	3.0 db
Space loss (22,000 nmi range)	189.0 db
Satellite antenna gain (earth coverage)	16.0 db
Circuit losses (diplexer, etc.)	1.0 db
Net transmission loss	172.5 db
Received signal power	-117.7 dbm
Receiver noise spectral density (5.0 db N.F.)	-169.0 dbm/Hz
IF noise bandwidth (20 kHz each filter)	43.0 db
IF noise power	-126.0 dbm
IF signal-to-noise ratio	8.3 db

is 28 db. Consequently, some degradation of the downlink to the ground station will occur. As seen in the downlink budget (Table 6), the transmitter power loss to uplink noise is 1.1 db and the receiver noise spectral density is increased by 2.3 db. In computing the transmitter power

Table 6. Satellite-to-Ground-Station RF Link Power Budget (f_c = 1547 MHz)

Parameter	Value
Satellite transmitter power (1 watt)	+30.0 dbm
Power loss to uplink noise	1.1 db
Circuit losses (diplexer, etc.)	1.0 db
Antenna gain (earth coverage)	16.0 db
Space loss (22,000 nmi range)	188.4 db
Ground antenna gain (5-ft dish)	26.0 db
Ground circuit losses (diplexer, etc.)	1.5 db
Net transmission loss	150.0 db
Received signal power	-120.0 dbm
Receiver noise spectral density (5.0 db N.F.)	-170.0 dbm/Hz
Uplink noise contribution	2.3 db
Data Tones Detection (40 and 120 kHz)	
Received data power (total signal power)	-120.0 dbm
Data filters noise bandwidth (20 kHz)	43.0 db
Data noise power	-124.7 dbm
Data SNR	4.7 db
Required SNR ($P_e = 10^{-5}$, 200 bits/sec)	-1.0 db
Margin	5.7 db

loss, the effective IF signal-to-noise ratio is 5.3 db. The decrease of 3 db results from the fact that the two 20-kHz data tone filters present an effective noise bandwidth to the transmitter of 40 kHz. These degradations can be tolerated on the downlink because of the large antenna gain available at the ground station.

2.5.4 Satellite-to-Ground Station

As shown in Table 6, only 1 watt of satellite RF power is required to relay the 200 bits/sec data from users to the ground station because of the availability of the 26-db gain ground station antenna. A power margin of 5.7 db exists for detecting the data with a 10^{-5} bit error probability. The required data signal-to-noise ratio (in the wideband tone filter noise bandwidth) of -1.0 db was derived in Section 2.3.1.

2.5.5 Other Data Rates

The data rates of 200 and 64 bits/sec will handle the estimated peak data requirements for surveillance in the North Atlantic ocean area in 1975. Using an earth coverage satellite antenna, these data rates are about the maximum that can be handled because of limitations on the output power from the solar array of the NAVSTAR satellites (see Section 4). The required transmitter power of 22 watts total (90 watts DC input power) is near the maximum achievable RF output. The data rates can be increased, however, by increasing the satellite antenna gain. If the beam pattern is changed from earth coverage to North Atlantic ocean coverage about 5 to 7 db increase in gain can be realized making possible up to a five times increase in data rate. Table 7 shows data rates for different combinations of user and satellite antenna gains. The data rates assume the satellite transmitter power is 22 watts with 20 watts used for the carrier transmitted to users and 1 watt for the carrier transmitted to the ground station (the remaining 1 watt is used for the satellite tracking data).

Table 7. Data Rates for Traffic Control

User Antenna Gain (db)	Satellite Antenna Gain	Data Rates[2] To User (bits/sec)	Data Rates[2] To Ground Station (bits/sec)
0[1]	Earth coverage (16 db)	32	200
0[1]	North Atlantic coverage (23 db)	160	1000
3	Earth coverage (16 db)	64	200
3	North Atlantic coverage (23 db)	320	1000

(1) May require 500 to 600 watts user transmitter power.

(2) Assumes 20 watts satellite transmitter power to users and 1 watt to the ground station.

3. SATELLITE TRACKING DATA LINKS

Data links from remote NAVSTAR ground tracking sites to a central ground station are used to transmit satellite tracking information received by the remote sites to a central station where computations of satellite ephemeris and oscillator drift corrections are made. The original design for these links is described in Volume IV, Section 4.9 of Reference 1. In that design, an L-band transponder on the NAVSTAR satellites was used to relay the tracking data. The transponder time-shared the 50-watt navigation transmitter with the navigation signal transmissions. Tracking data was relayed by the satellites between navigation signal transmissions. In the new design described here, this transponder is replaced by the transponder for relaying traffic control data (see Section 2.4.3). Since the transponder contains its own TWT output transmitter, the navigation transmitter is no longer required to relay the tracking data. As a result, the tracking data relay link is available on a full-time basis.

3.1 SATELLITE ACCESS

As with the traffic control data links, each satellite transponder is tuned to a different transmit-receive pair of frequencies. Remote sites tune their transmitter frequencies to operate with a given satellite, and the central receiving site has a receiver for each satellite being used. Actually, a single satellite will have the capacity to handle the data requirements from many remote sites since the tracking data rates required are very small. Access to a single satellite by two or more remote sites would be time-shared by those sites. Time synchronization between sites could be accomplished by the time information supplied with the navigation signal broadcasts; in any case synchronization is not a problem since large guard bands can be established between transmissions.

In a four-satellite network for navigation and traffic control in the North Atlantic not more than two remote tracking sites are required. A single satellite can handle the tracking data requirements of this network so that the other three satellites do not need to relay tracking data. The transponder in these satellites could have the third IF channel removed or not functioning. The central station would have one receiver to receive the time-shared transmissions from the two remote sites. A worldwide network of satellites would require only about four satellites for the tracking data relay, located appropriately around the globe to cover the various tracking sites. It may be desirable for redundancy to have all of the network satellites capable of relaying the tracking data. The transponder IF channel for any satellite could then be activated or deactivated via the command link to the satellites.

3.2 MODULATION-DEMODULATION TECHNIQUE

The modulation-demodulation technique for this link is coherent PSK, the most efficient technique and therefore that requiring the minimum satellite output power. Remote sites transmit data at 32 bits/sec. The data is first modulated onto a 512-Hz square-wave subcarrier (actually modulo-two added with the square wave) to remove the data modulation sidebands from the vicinity of the carrier. The square-wave subcarrier than biphase modulates the carrier with a low deviation index in order to leave sufficient power in the carrier to serve as a coherent reference for detection of the data at the receiver. The effective modulation rate is then 1024 bits/sec even though the data rate is only 32 bits/sec. An RF bandwidth of about 4 kHz is sufficient to pass the modulation sidebands.

The receiver acquires the coherent carrier with a phase-lock loop and the data modulated square-wave appears at the output of the loop phase detector. A bit synchronizer reconstructs the 32 bit/sec stream from the noisy square-wave subcarrier. The division of power between the carrier and the modulation is dependent on the modulation index. For biphase modulation $\cos^2\beta$ of the power remains in the carrier and $\sin^2\beta$ of the power goes into the data, where β is the peak modulation index in radians. Therefore, the index must be less than 1.57 radians to prevent complete suppression of the carrier. The actual index will be about one-half of a radian and the resulting division of power provides a 10-db signal-to-noise ratio in the carrier loop (with a 100-Hz two-sided loop bandwidth), which should provide a clean reference for the data. The data power is sufficient to give a 10^{-5} probability of information bit error. For coherent PSK, a 10^{-5} bit error probability requires a signal energy per bit-to-noise spectral density ratio of 9.6 db (Reference 5).

The remote tracking sites will require a data modulator and 500-watt transmitter operating into a 12-db gain L-band antenna. The central receiving site will require an identical 12-db receiving antenna, a phase-lock receiver, and a bit synchronizer operating on the 512-Hz square-wave subcarrier and data.

3.3 POWER BUDGETS

The power budgets for the RF links from the remote sites to the satellite and the satellite to the central receiving station are shown in Tables 8 and 9. The earth coverage satellite antenna is assumed. The uplink to the satellite is sufficiently strong so that degradation by uplink noise does not occur on the downlink. The required satellite transmitter power to relay the 32 bits/sec of tracking data is 1 watt.

Table 8. Remote Tracking Sites-to-Satellite RF Link Power Budget (f_c = 1650 MHz)

Parameter	Value
Remote site transmitter power (500 watts)	+57.0 dbm
Circuit losses (cable)	1.0 db
Antenna gain	12.0 db
Space loss (22,000 nmi)	189.0 db
Satellite antenna gain (earth coverage)	16.0 db
Circuit losses (diplexer, etc.)	1.0 db
Net transmission loss	163.0 db
Receiver signal power	-106.0 dbm
Receiver noise spectral density (5.0 db N.F.)	-169.0 dbm/Hz
IF noise bandwidth (20 kHz)	43.0 db
IF noise power	-126.0 dbm
IF signal-to-noise ratio	20.0 db

Table 9. Satellite-to-Central Site RF Link Power Budget (f_c = 1542 MHz)

Parameter	Value
Satellite transmitter power (1 watt)	+30.0 dbm
Power loss to uplink noise	0 db
Circuit losses (diplexer, etc.)	1.0 db
Antenna gain (earth coverage)	16.0 db
Space loss (22,000 nmi)	188.4 db
Central site antenna gain	12.0 db
Circuit losses (cable)	1.5 db
Net transmission loss	162.9 db
Received signal power	-132.9 dbm
Receiver noise spectral density (5.0 db N.F.)	-170.0 dbm/Hz
Uplink noise contribution	0 db
<u>Carrier</u>	
Modulation loss (mod. index = 0.5 radian)	1.1 db
Carrier power	-134.0 dbm
Carrier loop noise bandwidth (100 Hz)	20.0 db
Carrier loop noise power	-150.0 dbm
Carrier loop SNR	+16.0 db
Required loop SNR	+10.0 db
Margin	6.0 db
<u>Data Subcarrier (512 Hz square-wave subcarrier)</u>	
Modulation loss (mod. index = 0.5 radian)	6.4 db
Data power	-139.3 dbm
Data bandwidth (H = 32 bits/sec)	15.0 db
Data noise power	-155.0 dbm
Data SNR	+15.7 db
Required SNR ($P_e = 10^{-5}$)	9.6 db
Margin	6.1 db

4. SATELLITE DESIGN CHANGES

The addition of traffic control capability to the NAVSTAR satellites does not alter the basic design of the satellite as described in Volume IV of Reference 1 (Intelsat III modification). However, the weight of the satellite at launch increases by about 104 pounds, including 47 pounds of added propellant for the apogee motor. Nevertheless, the Thor-Delta launch vehicle is still capable of launching the heavier satellite as a 200-pound weight margin existed in the previous design.

The tracking data transponder will be replaced by the three-channel transponder which relays both the remote site tracking data and the full duplex traffic control data. The added weight is 12 pounds; the new transponder and diplexer weighs 16 pounds, the old 4 pounds.

The average DC power requirement for all of the satellite subsystems is 99.1 watts, after subtracting the 3 watts required by the removed tracking data transponder. The new transponder requires 90 watts of DC power. Therefore, the solar array output power must be increased to at least 199 watts (including 10 watts extra for added converter losses) to accommodate the new transponder on a continuous operating basis. The present solar array delivers 121.6 watts at beginning of life and 99.8 watts minimum after five years in orbit. Array capacity can be readily expanded to 125 watts minimum output after five years since room exists on each solar panel to add two more strings of solar cells. Array capacity can be increased further to better than 200 watts output after five years by increasing the length of the panels and adding another six strings to each panel. With 200 watts output, the weight of the power subsystem increases by about 45 pounds, including provision for larger battery capacity.

Some additional weight may be required for modifications to the satellite structure and certain subsystems such as positioning and orientation in order to accommodate the longer solar panels and the extra weight. However, the Thor-Delta vehicle is capable of launching another 100 pounds. This extra weight capability is more than adequate to handle any additional changes to the satellite design that may be necessary.

5. USER HARDWARE COSTS

A cost of \$12,400 is estimated for the traffic control transceiver based on a 300-watt output CW transmitter and a production run of 200 units. Including the preamplifier, the cost is \$13,300. The cost basis is shown in Table 10.

In calculating the cost of components other than semiconductors for the receiver and transmitter sections, it is estimated that 80 per cent of the component will cost an average of \$0.50 each and the other 20 per cent an average of \$10 each. The totals in Table 10 were thus reached as follows:

Receiver section:	263 (0.8)(0.50)	= 105
	263 (0.2)(10)	= 525
		630
Transmitter section:	129 (0.8)(0.50)	= 52
	129 (0.2)(10)	= 258
		310

The labor cost to assemble the receiver is taken as \$6.26 per component and to assemble the transmitter \$26 per component. Hence

Receiver section:	(309)(6.26)	= 1935
Transmitter section:	(158)(26)	= 4110

All of these factors are based on TRW's experience in producing similar units. All totals are rounded to \$5.

The 300-watt transmitter output is generated by two RCA tetrode tubes in cascade. These tubes are now special prototypes, but the supplier estimates that for a production run of 200 units, the cost including development would be about \$2100 per pair of tubes. These tubes are preferable to a TWT for use in an aircraft because of their light weight. A TWT generating 300 watts will weigh well over 150 pounds including power supply, compared to 20 pounds for the two tetrodes.

The RF preamplifier cost is not included in the total cost since this unit is part of the navigation receiver and was included in the costs for that receiver given in Reference 1. The cost of the preamplifier by itself is about \$850.

Table 10. Cost of Transceiver

	Semiconductors No.	Semiconductors Cost ($)	Other Components No.	Other Components Cost ($)
Receiver Section				
RF amplifier	5	290	60	
Mixer-converter	2	25	3	
IF amplifier	7	31	77	
Phase detector	4	25	8	
Loop filter	1	10	6	
VCO	5	20	25	
Tone filters			14	
Linear detectors	2	4	8	
Differential amplifier	1	8	4	
Summing amplifier	1	8	4	
Bandpass filter	2	10	10	
Zero crossing detector	1	8		
Integrate and dump	3	20	12	
Decide logic	2	16	4	
Power supply	10	20	28	
	46	495	263	630
Transmitter Section				
Gate	3	45	9	
Multiplier-driver	12	300	96	
Power supply	14	110	24	
	29	455	129	310

Exceptional Components	
Diplexer	$95
Preselector	30
Selectable TCXO	800
TCVXO	300
Frequency synthesizer	1100
Power amplifier (300 w)	2100
Blowers	75
	$4500

Total	
Receiver semiconductors	$495
Other receiver components	630
Receiver assembly labor	1935
Transmitter semiconductors	455
Other transmitter components	310
Transmitter assembly labor	4110
Exceptional components	4500
	$12,435

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