ORION Mobile Unit Design

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An overview of the design of the ORION mobile system is presented. System capability and performance characteristics are outlined. Functional requirements and key performance parameters are stated for each of the nine subsystems. A master design and implementation schedule is given.

I. Introduction

The ORION (Operational Radio Interferometry Observing Network) mobile system is being implemented in support of the NASA Crustal Dynamics Project (Ref. 1). Its purpose is to provide a means for measurement of lengths and orientation of vectors between sites located in areas of geophysical interest. This is accomplished by using Very Long Baseline Interferometry (VLBI) techniques operating at microwave frequencies using extragalactic radio sources (quasars).

With the recent emergence of the theory of plate tectonics (Ref. 2) and its potential for modeling motions on the Earth's surface, the need for precision geodetic measurements over long distances has increased. Experimental confirmation of the theory requires centimeter-level precisions over distances of 100-5000 km. This level of precision is also needed for earthquake research since it is believed that small motions of the Earth's crust may be precursors to episodic events (Ref. 3). Conventional surveying techniques are neither accurate enough nor economically feasible over distances in excess of 50 km, particularly if the terrain is mountainous or extends over large bodies of water. Therefore, there is a need for improved techniques capable of such measurements.

VLBI technology has progressed over the past decade to the point where centimeter-level accuracies are possible over the desired distances. Principal contributors to this advancement have been the advent of highly accurate atomic clocks, development of a suitable radio source catalog, development of a phase calibration system, and refined data processing techniques. A typical mobile VLBI system is shown in Fig. 1.

The extragalactic radio sources emit energy in the microwave frequency spectrum which is detectable by a suitably designed receiving system. In addition, the sources are located at such large distances that they exhibit no proper motion and therefore serve as a highly stable inertial reference frame. The signals are received simultaneously at each end of the baseline, converted to baseband and recorded on magnetic tape. The tapes are forwarded to a central processing facility where the signals are cross-correlated and the difference in time of arrival is determined. This information, coupled with source-position knowledge and calibration of error sources, permits accurate determination of the baseline length and orientation.

Project ARIES (Astronomical Radio Interferometric Earth Surveying) has provided the Research and Development needed to demonstrate the feasibility of mobile system interferometry as applied to geodetic measurement (Ref. 4). Based on these results and analysis (Ref. 5) it was determined that an operational system could be implemented. This article gives an overview of the design of the mobile system which has been developed within the past year.

II. Requirements

The technical performance requirement for the ORION system is as follows: The three-dimensional baseline measurement precision shall be $\leqslant$5 cm (1σ) for baseline lengths up to 5000 km. Length-only measurements shall be accurate to $<$2 cm.

The requirements are to be interpreted as the measurement repeatability or precision and not absolute accuracy. This level of performance must be achieved when operating with a co-site having a minimum antenna diameter of 9 meters, efficiency $\geqslant$0.50 at X-band and system temperature $\leqslant$40 K.

Given these requirements the next step is to determine the magnitude of each error contributor and to develop a design which will meet the requirements. Normally one of the criteria for an optimized system design is to have a balanced error budget; however, for the ORION system this turns out not to be a main consideration. The reason for this is that calibrations of several of the error sources are not under control of the mobile unit design.

The error sources associated with geodetic VLBI measurements are as follows:

(1) Signal-to-noise ratio (SNR).

(2) Instrumental delay calibration.

(3) Troposphere (wet and dry).

(4) Ionosphere.

(5) Antenna location.

(6) Clock stability.

(7) Source position.

(8) Polar motion.

(9) UT1.

The magnitude of error contributors (1) through (6) may be controlled either by choice of design parameters or by calibrations. Items (7) through (9) are calibrations not under control of the design. Reference 5 provides a detailed analysis of the interrelationship of these various error sources and Figs. 2 and 3 with accompanying Table 1 display the errors in bar chart form. It may be seen that a reasonably balanced error budget is achieved for a 300-km baseline and that the project requirements are met. For a 5000-km baseline the errors not under control of the design are dominant, resulting in a larger than desired measurement precision. As improvements are made in calibrations of the source positions and Earth platform parameters, the desired measurement precision will be possible without change in the mobile unit design.

A single quantity affecting the observation accuracy which involves the key design parameters is the signal-to-noise ratio. The relationship of these quantities is given in the Appendix.

In addition to measurement precision a number of other requirements must be met to achieve an operational design capable of worldwide performance. These are summarized as follows:

(1) The system must be economical to operate. Cost per continental U.S. site visit shall not exceed $5K.

(2) Mean time between failures shall be greater than 600 hours.

(3) The mobile unit shall be air transportable via C-130 and shall not require special permits for U.S. road transportation.

(4) No more than two persons shall be required to transport, assemble, operate and disassemble the mobile unit.

(5) The mobile unit shall be capable of sustained operations for periods up to one week without reprovisioning.

(6) Calibrations and observing sequences shall be fully automated, with the exception of tape changes.

There are a number of other requirements; however, these are the main drivers for the design. (The reader is referred to JPL internal document 1700-2, "ORION Mobile Station Functional Requirements," for further details).

The succeeding sections of this article describe the work completed, leading to a design which will meet the requirements.

III. Typical Operating Scenario

To acquaint the reader with the manner in which the mobile system can be utilized, a typical operating scenario involving one unit will be described. This is but one of several possible operating modes. It is assumed that the mobile configuration consists of two vans. One is called the electronics van, which contains the majority of the electronic equipment, the operations area and the crew amenities area. The other van is the antenna transporter, which consists of the antenna, antenna pedestal and servos, and the remaining electronics equipment. Other assumptions are a crew of two working a standard 40 hour work week, a 6-hour observing sequence and a site located 300 km from the departure point.

Monday – Prepare vehicles for transport.

Complete checklist

Drive to site or accommodation located nearby.

Tuesday – Establish communications with control center.

Position antenna transporter.

Erect antenna and interconnect vans.

Measure antenna position relative to geodetic marker.

Perform equipment readiness and calibration procedures.

Conduct observations.

Secure equipment.

Wednesday – Prepare equipment for transport.

Drive to next site or return to base.

Thursday – Repeat of Tuesday if at new site.

Friday – Repeat of Wednesday.

There are numerous details not included in this description; however, the main point is that, if desired, the unit can support a two-site-per-week schedule, using a two-person crew. Many other possibilities exist such as increasing the crew size to permit 24-hour observation schedules. This would only require a third vehicle to transport the crew or, if the site is remotely located, a recreational vehicle could be provided.

In developing the functional design, close attention has been given to the operational aspects. These have included ease of operations, maintainability and reliability with the philosophy that optimization of these parameters will best meet the project requirements of cost effectiveness over a 10-year life cycle.

IV. Tradeoff Studies

One of the studies performed early in the project (August 1979) was to determine the effects and sensitivities of antenna size and system temperature for both the fixed and mobile stations on the implementation and life cycle costs. Other variables included record time per observation, number of channels recorded, setup and teardown times for various antenna sizes. Some values were assumed to be fixed such as a minimum SNR per channel of 7 and source strength of 2 jansky.

Estimates of cost were made for both the implementation and operational costs, with the goal of minimizing the overall cost per site visit.

Certain assumptions were made such as:

(1) Thirty-two observations per site visit were required for delay measurement precision.

(2) An adequate star catalog would exist in 1982 to allow operation at any time.

(3) Barstow was used as the center point for tape shipping costs.

(4) One or more of the following base stations would be used:

Station	Antenna diam., m	System temp., K
DSS 13	26	30
OVRO	39 6	160
HRAS	26	160
Mojave	12.2	30

(5) Data (tape) handling costs were estimated as follows:

Correlator cost, $50/hr, two tape pairs/hr.	$25.00
Tapes, X2, @ $100 X 0.1 wearout factor	20.00
Clean, erase, certify tapes $2.5 X 2	5.00
Ship, round trip, Pasadena to Barstow	2.50
Total processing cost per tape pair	$52.50

The operating scenario included time to drive 160 km between sites; stop for fuel, tape shipment and pickup; setup and calibration time, operating time and teardown time.

Based on the above assumption, the study showed two things: (1) the better the base station the lower the per site cost, and (2) the shorter the setup and teardown times, the lower the per-site cost. A series of curves were developed to also show the optimum antenna size for each base station. Primarily, this showed that 4 to 5 m was optimum using a 130 K system temperature for the mobile station.

The design of the ORION mobile station requires a 5-m-diameter antenna and a 110-K system temperature. It is expected that a system temperature of 110 K at X-band can be achieved with current FET technology.

To calibrate for the ionospheric effects, ORION will also include an S-band link. The analysis by Wu (Ref. 6) indicates that the requirements on the S-band link are not very stringent. A system temperature in the range of 160-200 K at S-band would be appropriate. The analysis also indicates that precise data volume allocation between S- and X-band observations is not critical; an S/X data ratio between 1:2 and 1:4 is appropriate with a 160 K S-band receiver. Such a configuration, in conjunction with a typical 26-m base station on a 300-km baseline and recording 600 seconds per observation yields a 3-D baseline error due to SNR of 0.62 cm. When this is RSSed with all the other contributions to the overall error, it is somewhat insignificant. Reducing the record time by a factor of 4 would double the SNR error but would increase the overall 3-D baseline error only by 0.2 cm. In other words, data processing costs would reduce proportionately from $1680 per site visit to $420 by allowing the vector accuracy to degrade from 3.6 to 3.8 cm. This could be reduced even more by varying the record time for sources stronger than 2 jansky. Assuming ORION measures two sites per week for 10 years with an 80 percent utilization factor, this would amount to a $1,050,000 saving in data processing costs alone.

If the observation period per site could also be correspondingly reduced, then more sites could be visited per year, thereby reducing the cost per site even more. The above saving does not apply when a 9-m antenna is used as a base station. To maintain an SNR above 7, the 600-sec record time cannot be greatly reduced.

V. Electronics Design

The electronic equipment is required to perform the following functions:

(1) Receive and down-convert microwave energy at S and X-bands.

(2) Provide a highly stable clock.

(3) Produce an adequate signal-to-noise ratio (SNR).

(4) Provide an automated means to acquire, time tag and record the data.

(5) Produce a permanent record of equipment performance and generate real-time displays.

(6) Calibrate transmission media effects and record meteorological data.

(7) Furnish communications links to the control center.

To accomplish these functions the system design was divided into nine subsystems:

(1) Microwave (MWS).

(2) Receiver (RS).

(3) Data Acquisition (DAS).

(4) Frequency and Timing (FTS).

(5) Phase Calibrator (PCS).

(6) Monitor and Control (MCS).

(7) Water Vapor Radiometer (WVR).

(8) Antenna (AS).

(9) Facilities (FS).

The last two subsystems will be described in Sections VI and VII. The interrelationships of these subsystems are shown in block diagram form in Fig. 4.

A. Microwave Subsystem

The Microwave Subsystem consists of the S- and X-band antenna feeds, low-noise amplifiers (LNA) and cooling assembly. It performs the following functions:

(1) Receives the amplified S- and X-band signals from the antenna subsystem.

(2) Provides coupling for the S- and X-band phase calibration tones.

(3) Provides performance monitoring information to the Monitor and Control Subsystem.

The S-band operating frequency range is 2220-2320 MHz with a half-power bandwidth of 100 MHz. X-band operating frequency range is 8200-8600 with a half-power bandwidth of 400 MHz. Antenna efficiencies are $\geq$0.40 and $\geq$0.50 at S- and X-band respectively, and the polarization is right circular. System temperatures are $\leq$160 K and $\leq$110 K for S- and X-band. A preliminary vendor survey indicates these performance parameters can be achieved using commercially available equipment. The microwave equipment will be located on the antenna assembly in protective enclosures. Monitor and control will be provided via an RS-232C interface.

B. Receiver Subsystem

The Receiver Subsystem performs the following functions:

(1) Receives S-band signals from the Microwave Subsystem and downconverts to an intermediate frequency of 300 MHz with a half-power bandwidth of 100 MHz.

(2) Receives X-band signals from the Microwave Subsystem and downconverts to an intermediate frequency of 300 MHz with a half-power bandwidth of 400 MHz.

(3) Generates appropriate mixing frequencies using a reference signal supplied by the Frequency and Timing Subsystem (FTS).

(4) Provides performance status signals to the Monitor and Control Subsystem via an RS-232C interface.

(5) Supplies dc power to the Phase Calibration Subsystem.

Input signals will be supplied from the LNAs via coaxial cables within a range of -70 to -40 dBm. Reference frequency input will be 100 MHz at 13 dBm. The receiver will be located on the antenna transporter within a suitable enclosure. Monitor and control will be provided via a RS-232 interface.

C. Data Acquisition Subsystem

The Data Acquisition Subsystem (DAS) is a general-purpose digital recording device for sample data rates ranging from 0.25 to 8 MHz. The subsystem is the operational version of the Crustal Dynamics Project MK-III VLBI Data System. Primary inputs to the DAS are the S- and X-band IF signals and information for the ancillary data record provided by the Monitor and Control Subsystem. A detailed description of the MK-III Data System may be found in Ref. 7.

The DAS performs the following functions:

(1) Accepts the S- and X-band intermediate frequencies from the Receiver Subsystem.

(2) Provides 14 selectable center frequencies within the microwave bandpass.

(3) Downconverts energy on either side of the selected frequencies to 14 pairs of video bands.

(4) Provides video bandwidth selection for each pair of video bands.

(5) Formats and time tags the data.

(6) Provides real-time and non-real-time recording performance monitoring and diagnostics.

(7) Provides for remote control operation of the subsystem.

(8) Supplies computer and computer interface for the Monitor and Control Subsystem.

(9) Reproduces data for digital tone extraction and post-real-time processing or reduction.

(10) Provides redundant recorders.

(11) Determines total power within microwave bandpass.

The performance parameters of the DAS are:

Input Characteristics

(1) Input IF Frequencies:

S-band IF, 300-MHz center frequency

S-band bandwidth ±50 MHz (-3 dB)

X-band IF, 300-MHz center frequency

X-band bandwidth, ±200 MHz (-3 dB)

(2) IF Input Levels: -10 dBm to -42 dBm

(3) FTS Reference Frequency: 5 MHz 13 ±3 dBm

(4) Monitor and Control interface: RS-232

(5) Power Requirements: 105-130 Vac, 1Ø, 48-63 Hz, 1650 W average, 1900 W peak

Output Characteristics

(1) Selectable channel bandwidth in five steps each by a factor of two: 0.12 – 2.0 MHz.

(2) Selectable section on input spectrum to be output by any pair of channels: selectable in 10-kHz steps.

(3) Peak-to-peak gain ripple over 80 percent of the sample bandwidth of any channel: $\leqslant 0.5$ dB.

(4) Image rejection over 80 percent of sample bandwidth of any channel: $\geqslant 23$ dB.

(5) Deviation from gain linearity over output range -37 dBm to +3 dBm: $\leqslant 1\%$.

(6) Gain variation due to temperature change to be predictable within < 0.5 dB (1σ).

(7) Peak-to-peak phase ripple (deviation from linearity) in the frequency domain at 73°F: $< 10°$.

(8) Phase delay as a function of frequency to be predictable over allowable temperature and humidity range with uncertainty of 2° (1σ).

(9) Records:

Tape width, 1 in.

Number of tracks, 28

Longitudinal density, 33 kb/in./track at 135 ips

Recording code, NRZM in MI-III format

Control, local or remote via RS232C interface

(10) Monitor and Control interface: RS-232

Operating modes of the DAS are the following:

(1) Wideband – 28 tracks recorded in one pass, upper sideband outputs to first 14 tracks and lower sideband outputs to the remaining 14.

(2) Continuum – 14 tracks recorded per pass, only seven converters used.

(3) Multiline – 4 tracks recorded in each pass.

(4) Spectral – 1 track recorded per pass (Mark II compatible mode).

D. Frequency and Timing Subsystem

The Frequency and Timing Subsystem (FTS) provides one or more highly precise phase-coherent reference frequencies. It also provides accurate time information to the Data Acquisition Subsystem. Major assemblies include the Frequency Standard, Frequency and Timing Distribution Assembly, Time Sync Receiver and Time Sync Antennas.

The FTS performs the following main functions:

(1) Provides highly stable frequency reference.

(2) Distributes reference frequencies.

(3) Provides means to establish accurate epoch time.

(4) Distributes timing pulses.

(5) Monitors subsystem performance.

A hydrogen maser will be used for the timing standard. Frequency stability requirements are $< 1 \times 10^{-14}$ for time periods > 60 sec up to 86,400 sec. The standard is required to reach this stability four hours after arrival on site, which necessitates operating the unit and maintaining temperature control while in-transit. Time offset calibration will be accomplished using a global positioning receiver. The subsystem will supply 1 pps and 5 MHz signals to the DAS, Monitor and Control Subsystem, and Phase Calibration Subsystem.

E. Monitor and Control Subsystem

The Monitor and Control Subsystem (MCS) performs the following main functions:

(1) Provides the central control point for the station.

(2) Provides schedule input via floppy disk.

(3) Prepares the ancillary data record.

(4) Provides operator input-output via CRT terminal.

(5) Generates antenna pointing commands.

(6) Performs station calibration and malfunction diagnosis.

(7) Monitors weather conditions.

(8) Monitors subsystem performance.

(9) Provides operational communications.

The function of providing the central operating point for the station included control of all subsystem operating modes and display of all subsystem status and alarm messages. The ancillary data record consists of meteorological data, water vapor radiometry data, phase calibration data, end-to-end system performance verification data, and other data as appropriate for delivery to the user with the VLBI data from the Data Acquisition Subsystem. Generation of antenna pointing commands includes commands for conducting the calibration and observation sequence.

Station calibration includes determination of antenna axis intersection location based on site survey data and all periodic subsystem performance verification test. Malfunction diagnosis includes special operational sequences conducted after an abnormal condition is detected during an operational sequence or station calibration. Weather monitoring includes temperature, pressure, humidity, and wind speed. All of these except wind speed are for inclusion in the ancillary data record. Rapid communication includes those transceivers and antennas necessary to provide 90% reliable communications to the point from which the experiment is being coordinated. It specifically excludes the equipment for nonoperational communication between the antenna and electronics transporter prime movers (which are included in the Facilities Subsystem).

The MCS utilizes the DAS HP-1000 to perform its functions. Subsystem interfaces are via RS-232C. Operator interface will be via keyboard and CRT, with hard disk supplied for program storage. Floppy disk will be used for storage of the ancillary data record. Routine status displays will be provided with detailed subsystem performance available upon request.

Meteorological data will be measured using one of several commercially available instrument packages. The data will be a part of the ancillary data record.

Communications will be via a combination of land line radio-telephone and HF transceivers for continental U.S. operations. Foreign country operations may require tailoring the communications capability to meet requirements.

F. Phase Calibration Subsystem

The Phase Calibration Subsystem (PCS) will provide calibration tones at S- and X-band which permit monitoring of the respective radio source signal paths. The tones will be digitally sampled and recorded simultaneously with the signals and will be detected and displayed in real-time by a digital tone extractor.

The PCS performs the following functions:

(1) Generates phase-stable signals at S- and X-band which are coherent with the FTS references.

(2) Couples the signals at the proper level into the S- and X-band low noise amplifiers.

(3) Detects and displays the calibration signal phase and amplitude for the purpose of real-time monitoring.

(4) Monitors electrical length of the frequency reference cable to the antenna transporter.

(5) Monitors subsystem performance and reports to MCS via RS232C interface.

The phase calibrator generates a phase-stable comb pattern at S- and X-band which is injected at a point preceding the low-noise amplifiers. Spacing between tones is adjustable to permit presence of several tones within the video passband.

G. Water Vapor Radiometer Subsystem

Figure 5 illustrates the Water Vapor Radiometer Subsystem (WVR) functions and interfaces. The WVR performs the following main functions:

(1) Determines water vapor apparent brightness temperature.

(2) Monitors water vapor radiometer performance.

The radiometer will be located on the backside of the main antenna with an opening provided to allow viewing along the line-of-sight of the main beam. This eliminates the need for a separate antenna pedestal and its attendant electronics and pointing software. Operating frequencies will be 20.7 and 31.4 GHz with a halfpower bandwidth of 7 degrees and a beam efficiency of >97 percent. Integration time will be variable and selectable from 0.1 to 10 sec. An absolute accuracy of 2.0 K (rms) is required.

VI. Antenna Transporter Design

A. Requirements

The more salient features of the functional requirements driving the design of the antenna/transporter are as follows:

(1) No more than two people are required for any phase of the ORION mobile station operation. This includes setup of the antenna.

(2) No more than four hours shall be required to prepare the station for operation after arrival at a prepared site. Therefore, approximately two hours is the maximum time allotted to positioning, assembly and alignment of the antenna.

(3) The vehicles must be transportable by C-130 aircraft. While on the highways, they must stay within the standard envelope of 13.5 ft high by 8 ft wide.

(4) The location of the axis intersection of the antenna must be known within 0.5 cm of an established monument.

(5) Five meter antenna with system efficiency of $\geqslant 50\%$ at 8.6 GHz and $\geqslant 40\%$ at 2.3 GHz.

B. Error Budget

An error budget was prepared to allocate dish distortion losses and pointing error losses and to proportion the phase center location allowance among the various components and error contributing factors. Estimates received from the Microwave Subsystem were that an RF efficiency, excluding central blockage and quadripod blockage, would be approximately 0.72. Assuming a 5 percent area blockage for subreflector and quadripod, the balance of the required 50 percent overall efficiency allotted to dish distortion and point error is:

$$\frac{0.50 \text{ (target overall)}}{0.72 \text{ (RF)} \times (1 - 0.05)^2 \text{ (central and quad blockage)}} = 0.77$$

Figure 6 shows the relationship of allowable pointing error to the rms dish distortion for the 77 percent at 8.6 GHz. Thus, as indicated in Fig. 6, with a likely rms dish distortion of 1.2 mm (including manufacturing, gravity and wind distortions), the allowable error for pointing is approximately 0.083 degrees.

Table 2 shows the estimated contribution for the various sources of error.

With regard to the 0.5-cm antenna location with respect to a local monument, the plan is to construct a locator arm which is connected to the antenna pedestal and is positioned to be in contact with the established monument (by means of a spherical seat or similar connection).

The arm, Fig. 7, will be provided with angular encoders to measure the azimuth and elevation angle of the device and a linear transducer to measure the arm extension. Thus, the vector relationship between the reference point on the antenna pedestal and the monument may be determined and monitored.

An additional feature shown in Fig. 7 is the north-seeking gyro. This may or may not be located as shown on the locator arm but will be provided to enable setup and determination of true north quickly. There is no guarantee that a clear sky will enable us to initially align the antenna to the sun as is done with ARIES antenna.

The rectangular coordinates of the phase center with respect to the monument (Fig. 8) are X_T, Y_T, Z_T. The actual phase center components will also depend on the errors from six transducers, namely,

ϵ_X level about x axis

ϵ_Y level about y axis

ϵ_L length of locating arm

ϵ_A arm azimuth angle

ϵ_E arm elevation angle

ϵ_G gyroscope north-seeking compass

The actual phase center components will also include displacements caused by:

(1) Deflection of structure from wind.

(2) Deflection of ground at trailer supports.

(3) Thermal deflection of structure from ambient temperature change.

(4) Thermal deflection of structure from differential temperature between sun and shade sides.

The measured phase center coordinates including level errors are:

$$x_T = -c\epsilon_y + \ell \cos(\Theta_E - \epsilon_Y \cos\Theta_A + \epsilon_x \sin\Theta_A) \cos(\Theta_A - \epsilon_y \sin\Theta_E \sin\Theta_A - \epsilon_x \sin\Theta_E \cos\Theta_A)$$

$$y_T = c\epsilon_x + \ell \cos(\Theta_E - \epsilon_y \cos\Theta_A + \epsilon_x \sin\Theta_A) \sin(\Theta_A - \epsilon_y \sin\Theta_E \sin\Theta_A - \epsilon_x \sin\Theta_E \cos\Theta_A)$$

$$z_T = c + \ell \sin(\Theta_E - \epsilon_y \cos\Theta_A + \epsilon_x \sin\Theta_A)$$

The measured phase center coordinates including errors on azimuth, elevation, and length encoders of locating arm are:

$$x_T = (\ell \pm \epsilon_\ell) \cos(\Theta_E \pm \epsilon_E) \cos(\Theta_A \pm \epsilon_A)$$

$$y_T = (\ell \pm \epsilon_\ell) \cos(\Theta_E \pm \epsilon_E) \sin(\Theta_A \pm \epsilon_A)$$

$$z_T = C + (\ell \pm \epsilon_\ell) \sin(\Theta_E \pm \epsilon_E)$$

The errors x_T, y_T, z_T are obtained by subtracting their nominal values from the above measured values.

Representative values are obtained by taking $\Theta_A = 0$, $\Theta_E = 45°$, $\ell = 2000$ mm, C = 4800 mm, phase center locked at zenith.

Table 3 summarizes the error budget for the encoder accuracies as shown on Fig. 7 and the representative values listed above.

C. Antenna-Transporter Description

It became clear early on in the project that if the goal of low cost was to be achieved, an extensive R&D effort for antenna development could not be entered into. Thus, commercially available components are to be used to the maximum extent possible.

Figures 9 and 10 show the proposed general arrangement of the antenna transporter. The trailer (1) is approximately 40 ft in overall length, has sides (2) which fold down mechanically to provide working platforms, and a cover (3) which is retractable by rolling forward on a drum (4). The trailer provides support for a commercially available pedestal (5), which is erected into the vertical position and lowered for the transporting mode by means of hydraulic cylinders (6).

The reflector is 5 meters in diameter, f/d of 0.34, and is a fiberglass layup in five pieces. The center piece (7) is permanently mounted to a yoke structure (8). The quadripod (9) and feed (10), along with the center piece of the dish, remains permanently attached to the yoke-pedestal assembly; thus, there is no need for time-consuming alignments at each setup.

The remaining dish quadrants (11) are assembled in halves on erection aids which are positioned near the pedestal at setup (Fig. 11). The already upright (and pointed to zenith) pedestal, yoke and center dish assembly is moved to zero degree elevation, engaging fasteners permanently moulded into the reflector. A turn of an allen-head wrench connects the dish halves by means of the aforementioned fasteners, which are over-center, clamping devices. The assembly is then plunged 180 degrees in elevation and the other dish half is similarly connected.

The assembled, erected antenna is shown in Fig. 12. The appropriate leveling outriggers (13) are provided on the pedestal. The locator arm (14) is shown mounted at the aft end of the pedestal for ease of removal for protection during shipping.

VII. Facilities Design

A. Scope

The facilities portion of the ORION project has been defined to include the electronic van and all support utilities.

B. Environmental Requirements

The first step in the design of the facilities was to establish the environmental requirements, which were determined to be that the mobile station must be able to operate under worldwide conditions. To develop environmental specifications for these conditions, the MIL-STD-210B "Climatic Conditions for Military Equipment" was used as a guide. From this starting point the following environmental requirements (Table 4) were developed for the project.

1. **General.** The mobile station electronics van shown in Fig. 13 will house the major electronics equipment, including the maser, and will also provide living quarters and amenities for the two station operators. Figure 13 shows the layout of the van interior. The van will be 33 feet in length and eight feet in width, with a clear height of eight feet. On the road it will have a height of under 13 feet 6 inches. Upon removal of the wheels and suspension system, it will be transportable on a C-130 aircraft. To minimize road shock to the electronic equipment, an air ride suspension system will be utilized. The construction details of the van will conform to standard commercial practice in the industry.

2. **Electronics area.** The primary concern in planning the layouts of the van electronics area was to provide for efficient and convenient operation. For maintenance purposes full access to the rear of the equipment is provided without moving the racks so that all equipment can be rigidly and permanently anchored. Due to temperature sensitivity, the maser is installed in an area separate from the operations area.

Storage space has been provided for 48 tape reels, which is adequate for one operational cycle. The reels are to be stored in sealed cans to prevent degradation due to high humidity. Space for storage of electronic spares is also provided within the van, and other spares can be stored in containers and placed in racks under the van.

3. **Living quarters.** The living quarters are separated from the operations area and provide suitable amenities to support the operators. These include shower, toilet facilities, microwave oven, refrigerator, bunks, storage space for personal effects, and space for consumables for a period of one week.

4. **Heating/ventilation/air conditioning (HVAC).** The entire electronic van will be air-conditioned, and it is planned to provide three air-conditioning zones: the living quarters, the electronic operations area, and the maser area. The trailer shell is designed to provide a well-insulated thermal barrier between the outside environment and the three air-conditioning zones.

These zones provide successive layers of environmental isolation for the critical maser area, which will be heavily insulated and will be controlled to ±0.1°C. The electronic operational area serves as an air lock to the maser zone. The operational area will be temperature-controlled to ±2.8°C, with minimum humidity control to maintain a range of 20 to 80 percent. The living quarters, in turn, serve as an air lock for the operational zone. This zone may experience high humidity loads due to the presence of people and their activities (i.e., showers and cooking). Exhaust fans will be used to minimize the humidity in this area. The living quarters will also be controlled to ±2.8°C. Finally, a small air lock is provided to shield the trailer interior from outside temperature, wind, dust and moisture.

The heating, ventilating, and air conditioning (HVAC) system utilizes two compressors. A small precision unit cools the maser compartment and is capable of operating on batteries while the van is being moved. The larger unit air-conditions both the operations area and the living quarters, utilizing two air-handlers. In case of failure of one air-handler, the air flow can be dampered to assure air flow to the operations area. The HVAC equipment will provide the interface between the monitor and control systems to indicate the operational status of all equipment. No air conditioning is required on the antenna trailer.

5. **Fire protection.** Ion-type smoke detectors and a Holon fire suppression system will be installed.

6. **Power**. Two 480-volt, 3-phase, 60-hertz diesel-driven generators will be provided to supply the stations' power requirements. Each unit will be capable of supplying the full station load to provide 100 percent redundancy. AC/DC power supplies will provide power to the electronic equipment. In addition, a battery bank will be provided to operate the maser and its air-conditioning system for a 24-hour period. The battery bank will have the capability of being charged from 50-cycle and 400-cycle sources, the latter being available during air transport. In addition, it will be possible to operate the entire station from a 60-cycle exterior source. The possible use of a 50-cycle source is presently being studied.

The starting of the diesel generators at low temperatures will be achieved either through the use of a small auxiliary engine-driven generator or utilizing compressed air if the battery requirements prove excessive.

All power equipment will interface with the Monitor and Control Subsystem to provide operational status of all the equipment.

7. **Lighting.** Interior lighting will utilize fluorescent fixtures; exterior area lighting will consist of incandescent fixtures permanently mounted on the van and the antenna trailer.

VIII. Schedules

The master schedule is shown in Fig. 14. The system design and subsystem functional designs will be completed by October 1980. Antenna transporter fabrication will commence in October 1980 with completion scheduled for June 1981. Facilities procurement is not scheduled until FY 82 due to funding limitations. However, electronics subsystems will be processed and integrated in FY 80 and FY 82. System test and operations training will begin in August 1982 and the first ORION mobile unit will be transferred to operations in October 1982. All succeeding mobile units will be fabricated by a system contractor beginning in FY 83.

Table 1. Estimated measurement accuracies

Parameter	Estimated accuracy
Baseline center latitude	ϕ = 35 deg
Baseline orientation	Arbitrary
Antenna diameters	9 m, 5 m
System temperatures	
S-band	40 K, 160 K
X-band	40 K, 110 K
Antenna efficiencies	
S-band	0.5, 0.4
X-band	0.5, 0.5
Source strength	2 jansky
Integration time per observation	600 s
Channel bandwidths	7 × 2 MHz per sideband per S- or X-band
Span bandwidths	
S-band	100 MHz
X-band	400 MHz
Clock stability	$\Delta f/f$ = 10-14 (t > 100 s)
Zenith dry troposphere,	0.5 cm, each site (systematic)
wet troposphere	
Bias	Immaterial
Systematic	0.5/$\sqrt{2}$ cm, zenith, each site
Random	0.5/$\sqrt{2}$ cm, zenith, each site
Ionosphere	Calibrated by S/X observations
Polar motion	30 cm
UT1	0.6 ms
Source position	0.01 arcseconds
Antenna location	0.5 cm at mobile site only
Instrumental delay	0.2 cm, each site
Number of observations	32
Number of solved for parameters	16 (baseline components and clock parameters)

Table 2. Pointing error budget

Alidade pedestal	0.065 deg
Encoders	
Servo	
Orthogonality of axes	
Compliance under 30 mph wind	
Antenna angular changes	
Bending deflection of structure from wind	0.0078
Bending deflection of structure from temp.	0.033
Trailer support shift from 30 mph wind	0.0176
Trailer level instrument	0.0166
Gravity direction	0.0166
Latitude	0.004
Longitude	0.004
North seeking gyro compass	0.025
Total error, RSS	0.083

Table 3. Phase center location error budget

Error source	x	y	z	x	y	z
Levels	$3386\ \epsilon_y$	$3800\ \epsilon_x$	$1414\ \epsilon_y$	0.985	1.105	0.411
Arm encoders	$1414\ \epsilon_E + 0.7\ \epsilon_l$	$1414\ \epsilon_A$	$1414\ \epsilon_E + 0.7\ \epsilon_l$	0.447	0.411	0.447
Gyro compass		$1414\ \epsilon_G$			0.617	
Trailer feet wind loading		1.91			1.91	
Structure wind loading		0.498			0.498	
Structure temp., $\Delta T = 52°C$			3.43			3.43
Structure temp., $\Delta T = 5.5°C$	1.72	1.72		1.72	1.72	
RSS vector sum = 4.99 mm				2.032	2.937	3.483

Table 4. Mobile station environmental specifications

External conditions	Operating	Nonoperating
High temperature	45°C	53°C
Low temperature	-29°C	-45°C
Wind speed	48 km/h	64 km/h while in transit; 193 km/h in stowed condition
Humidity		
with high temperature	Maximum 100% relative Humidity (RH) minimum 3% RH, 46°C	100%, 24°C (24 h)
with low temperature	100% RH, -29°C	100%, -45°C
Rainfall	N/A	2.54 cm/h
Ice accretion	N/A	7.5 cm glaze (specific gravity 0.9)
Snow load	N/A	97.6 kg/m
Hail	N/A	2.54 cm with antenna covered
Altitude		
Maximum	3048 m	15,240 m
Minimum	Sea level	Sea level
Sand and dust	0.15 GMS/M, 150	Raised level 1.0 GMS/M, 75-1000
Lightning and static charge	Provide ground	Provide ground
Fungus	MIL-V-173 c	MIL-V-173C
Salt spray	Coastal conditions	Coastal conditions
Shock and vibration	Air ride suspension and vibration isolators	Air ride suspension not applicable during air transport
Internal conditions	**Operating**	**Withstanding**
High temperature	27°C	66°C
Low temperature	16°C	-45°C
Temperature range	+1.1°C	93°C
Humidity	20% to 80% RH	Exterior conditions
Fungus	MIL-V-173C	MIL-V-173C
Hydrogen maser	26 ±0.1°C (For t > 16 m)	22-26 ±1°C

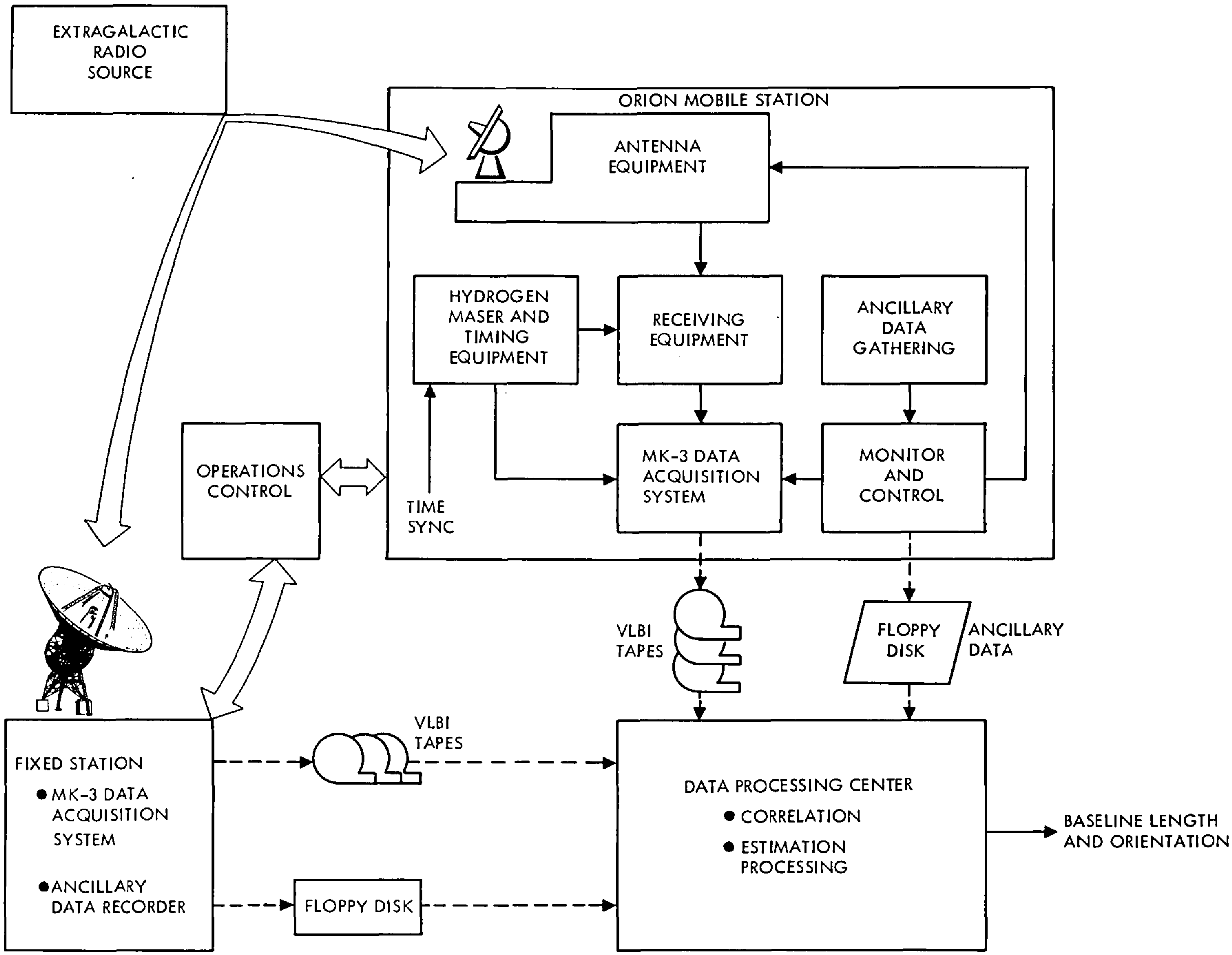

Fig. 1. ORION system, simplified block diagram

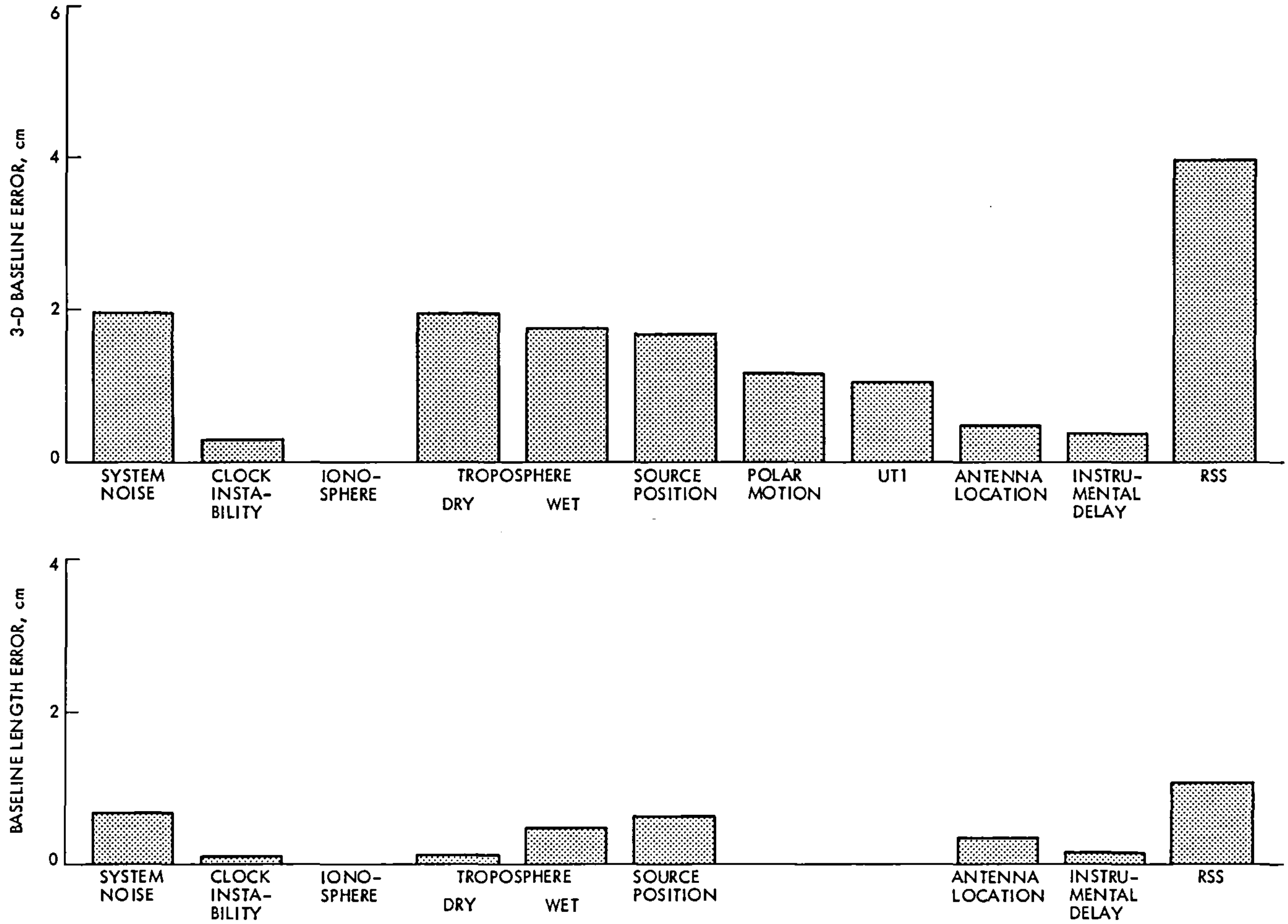

Fig. 2. Baseline vector and length estimation errors (300 km baseline)

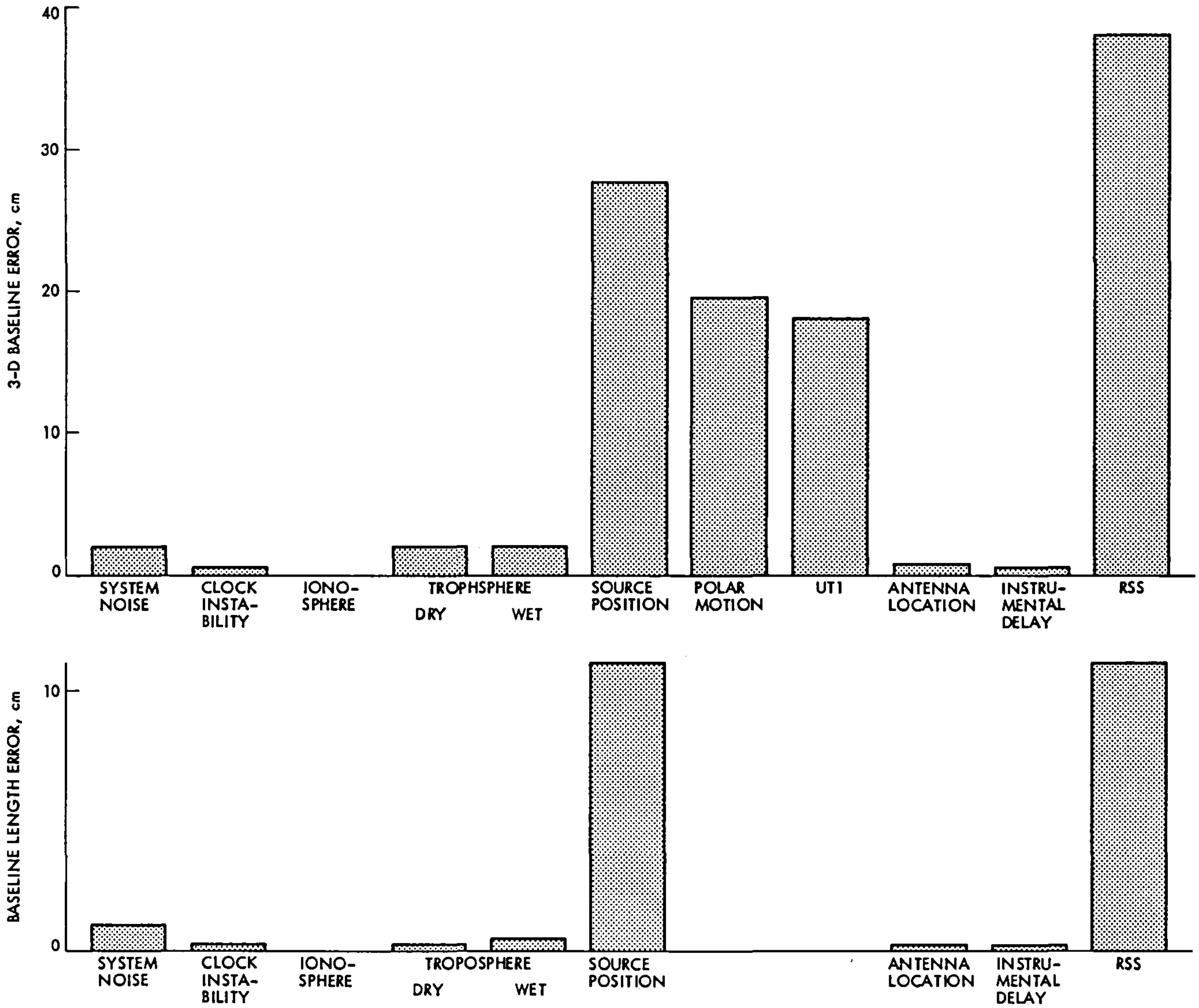

Fig. 3. Baseline vector and length estimation errors (5000 km baseline)

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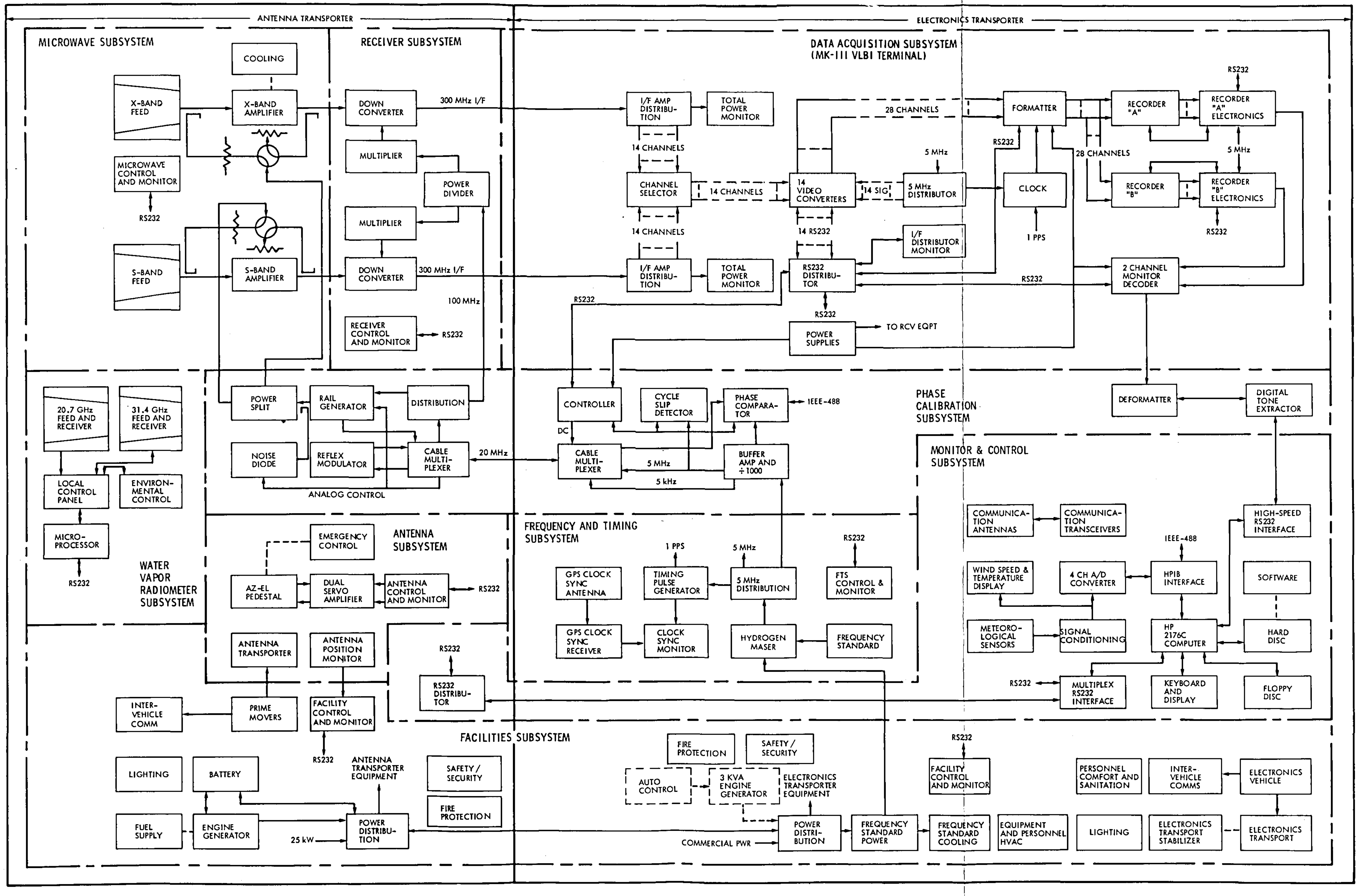

Fig. 4. Mobile station block diagram

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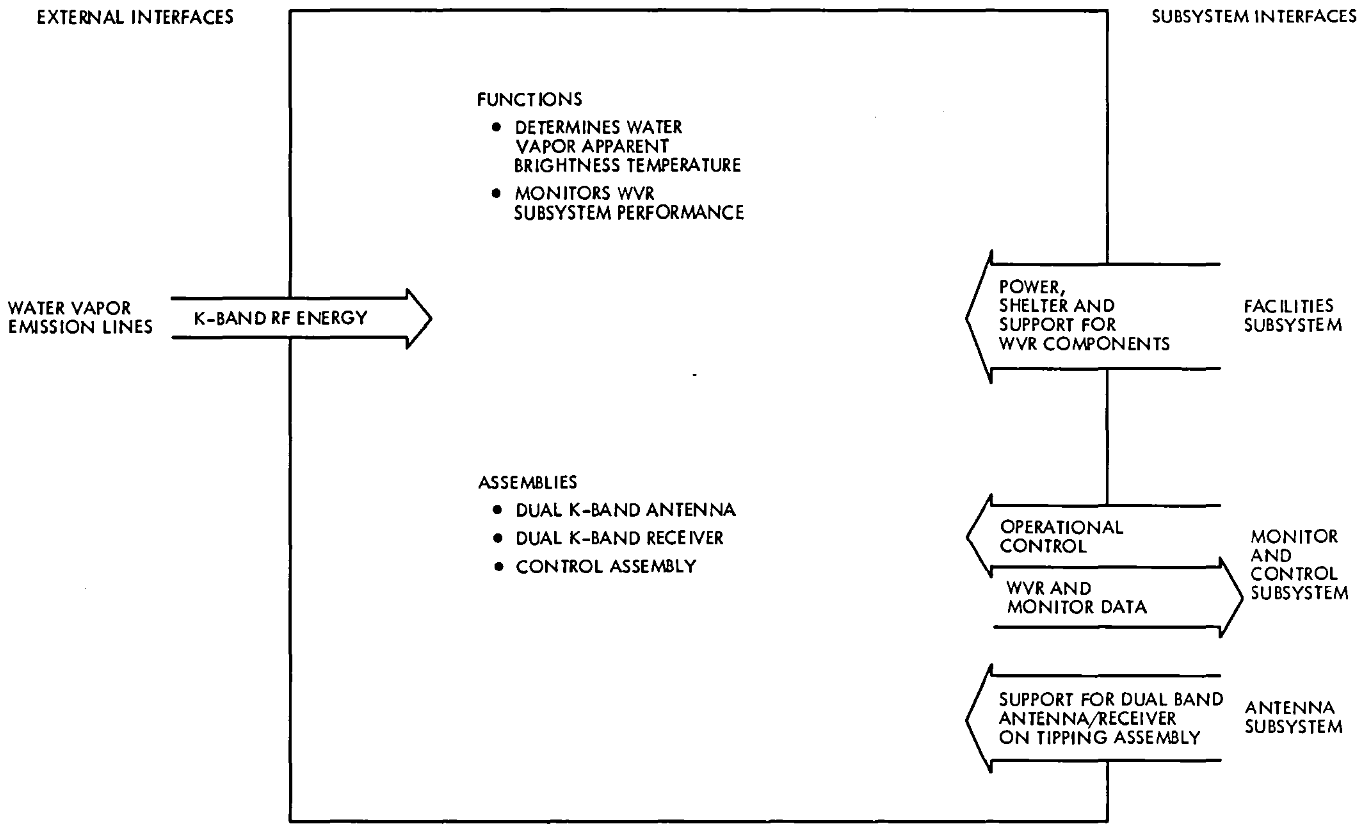

Fig. 5. Water vapor radiometer subsystem, function and interfaces

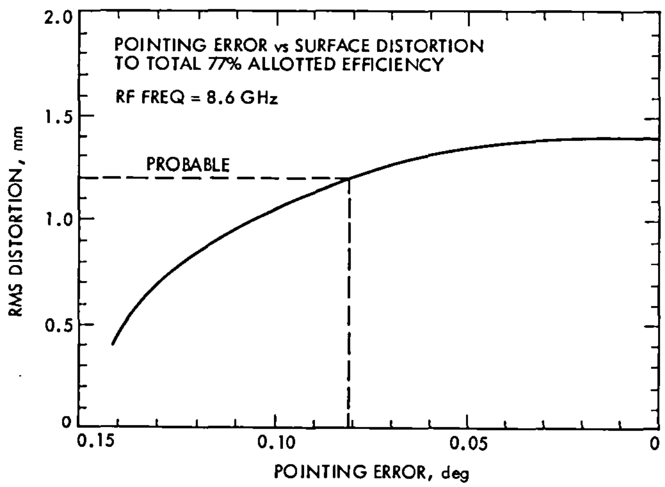

Fig. 6. Pointing error/surface distortion

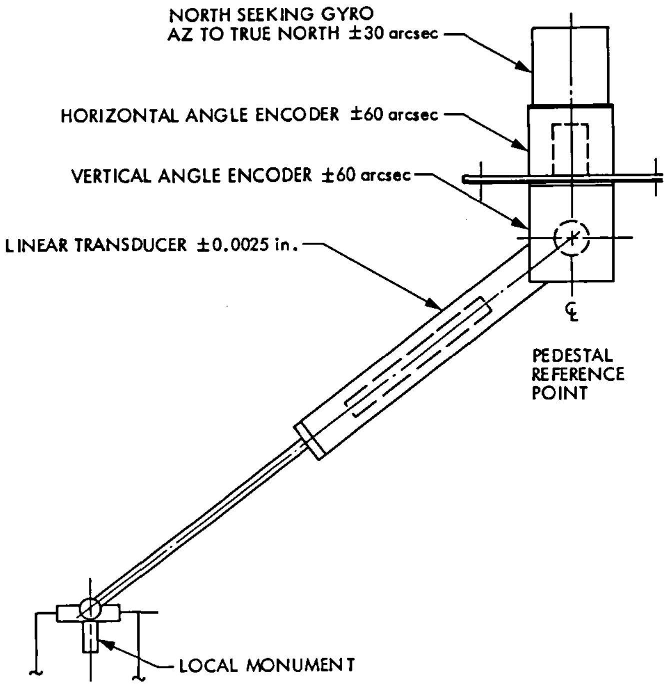

Fig. 7. Antenna transporter locator arm

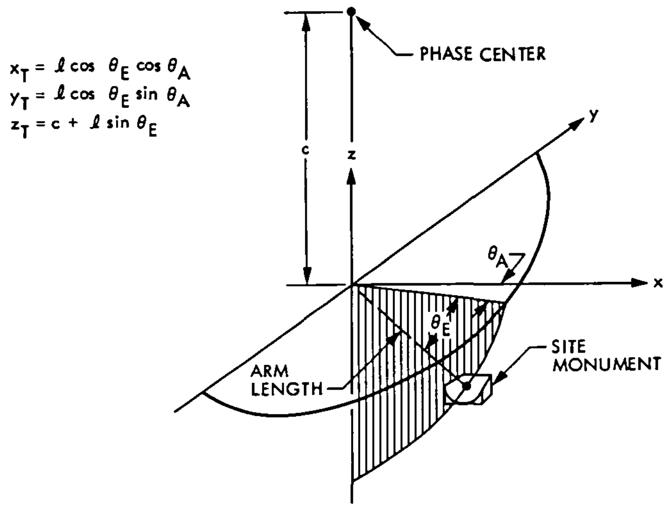

Fig. 8. Phase center/monument coordinates

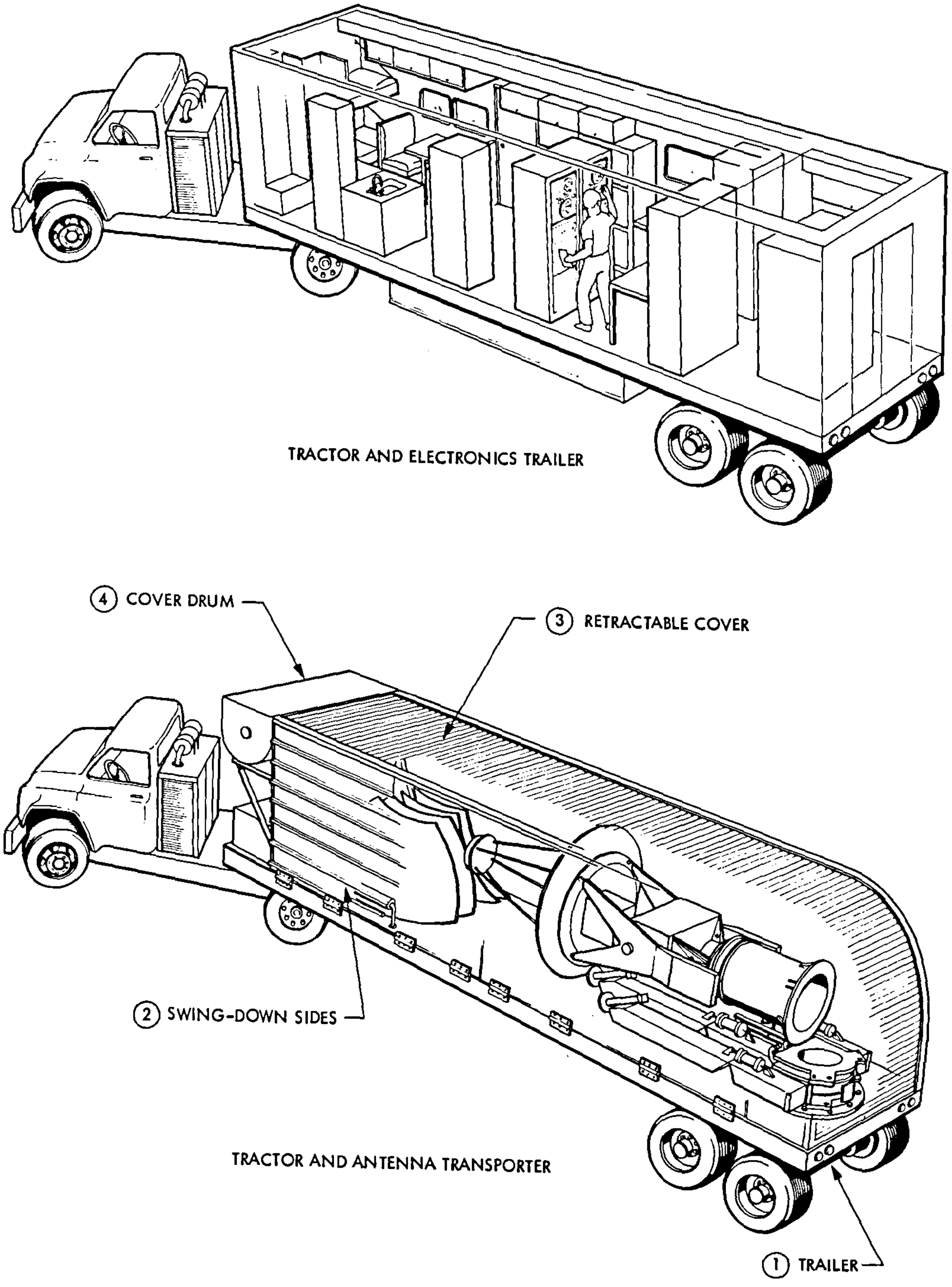

Fig. 9. General arrangement, antenna/facilities subsystem

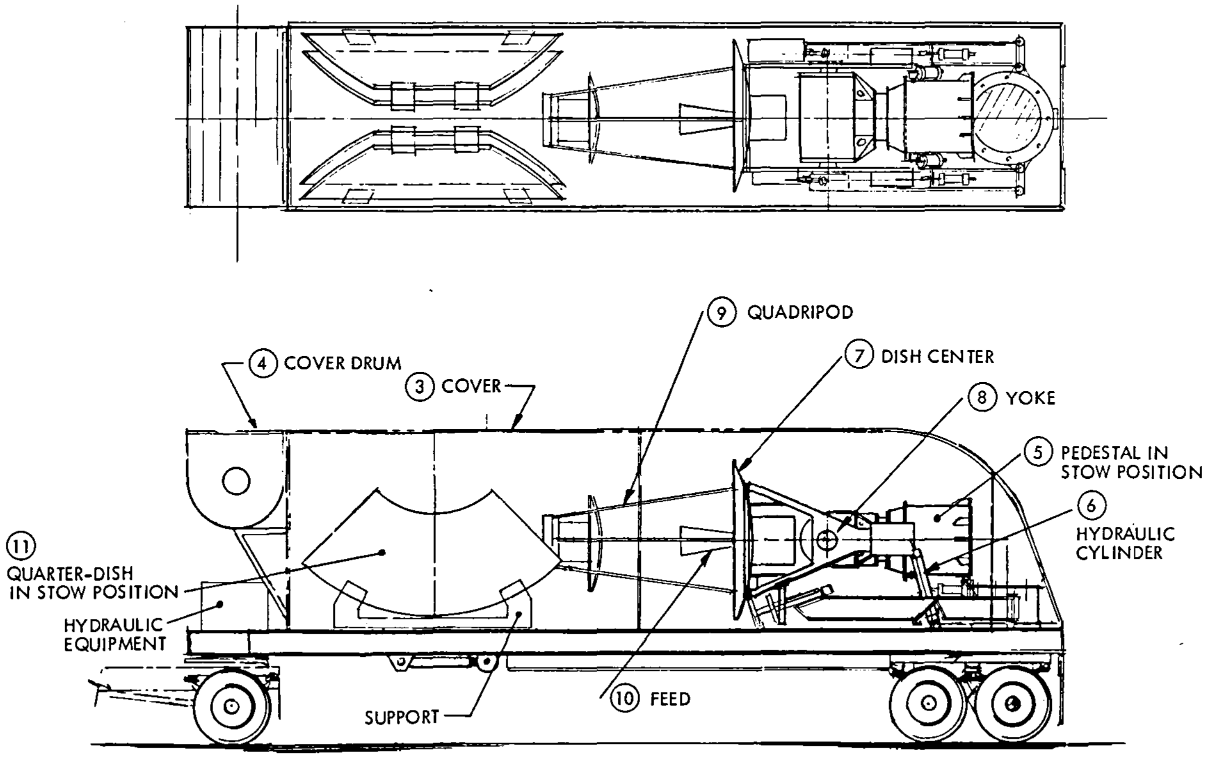

Fig. 10. Antenna transporter

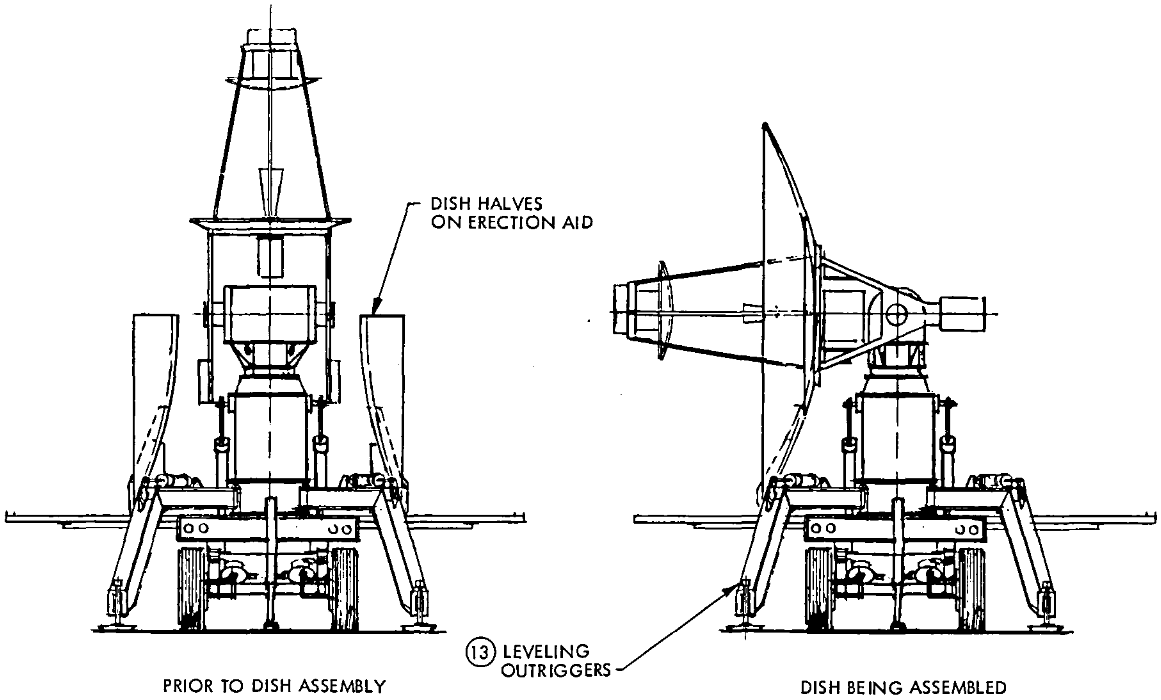

Fig. 11. Antenna transporter

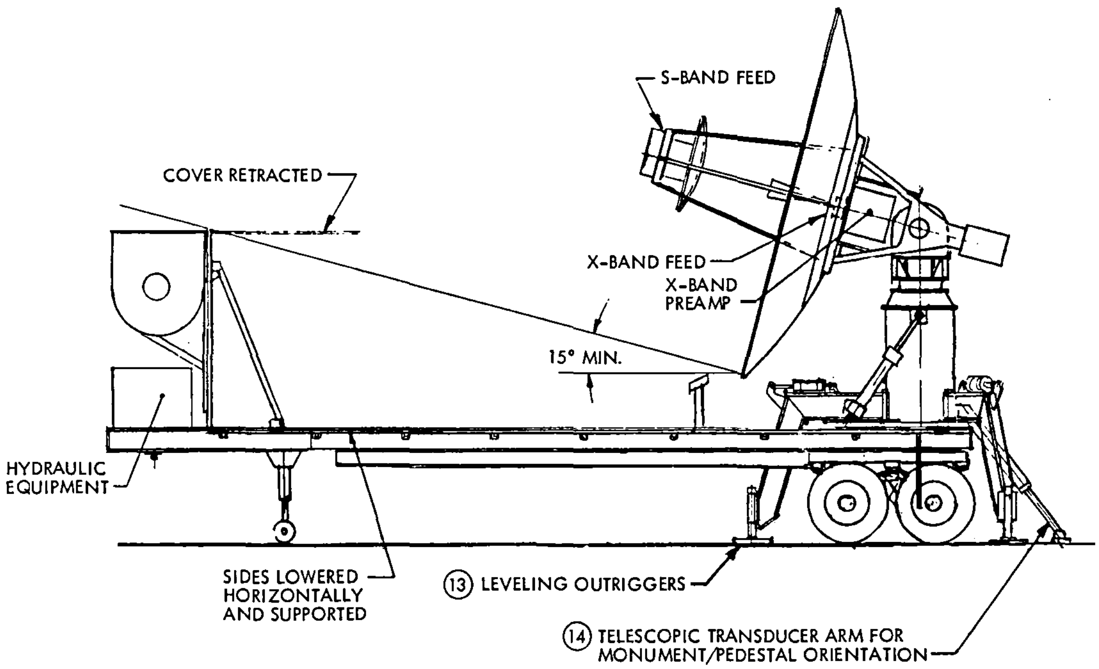

Fig. 12. Antenna transporter, operating mode

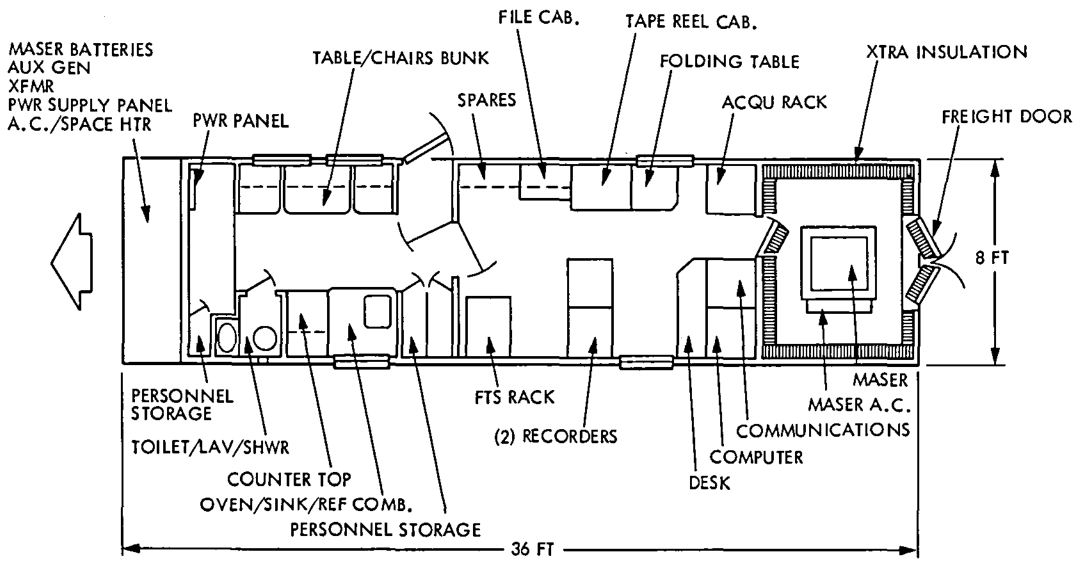

Fig. 13. ORION mobile station, electronics trailer

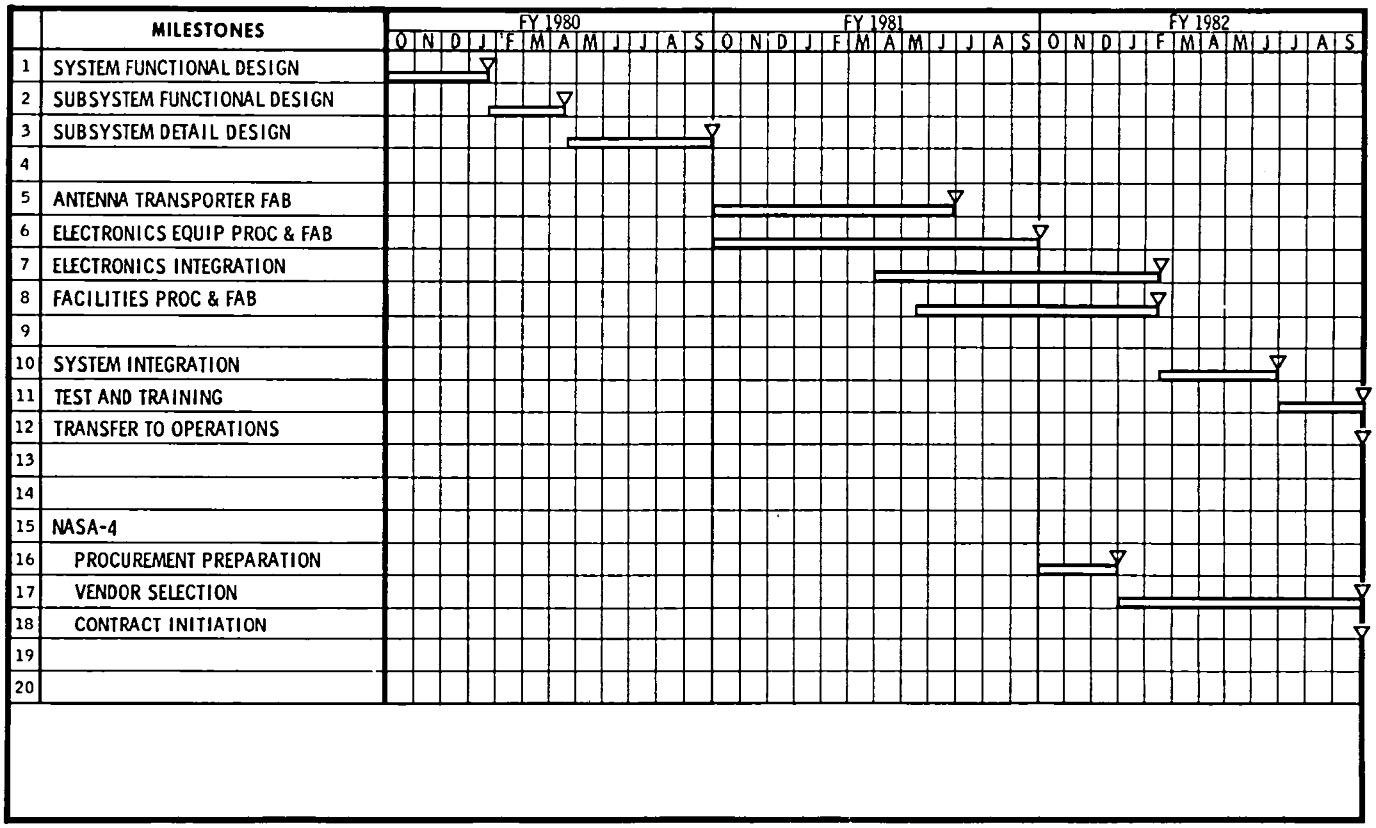

Fig. 14. ORION master schedule

Appendix
Signal-to-Noise Ratio

The signal-to-noise ratio (SNR) is defined as the ratio of the correlated fringe amplitude to RMS noise. For the case of two-level digitization, as used in the MK-III data acquisition system, the SNR at peak amplitude in a given channel is given by:

$$SNR_p = A \frac{1}{\sqrt{2}} \frac{2}{\pi} \gamma_v \sqrt{\frac{T_{A,1} T_{A,2} 2BT}{T_{S,1} T_{S,2}}} \qquad (1)$$

where

A = 0.8 (this conservatively accounts for unknown losses due to imperfect filter responses, unequal bandpass centering, etc.)

$1/\sqrt{2}$ = this factor accounts for heterodyning of the fringe phase in the correlator (lobe rotator)

$2/\pi$ = this factor accounts for loss due to two-level digitizing

γ_v = fraction of the correlated flux density out of the total source flux density

$T_{A,1}, T_{A,2}$ = antenna temperatures, K

$T_{S,1}, T_{S,2}$ = system noise temperatures, K

B = channel bandwidth, Hz

T = integration period, sec

Equation (1) is the SNR for a single correlation function at the delay lag near the correlation peak. In actual practice, energy from all lags within the main correlation lobe and nearby sidelobes is utilized, resulting in a $\sqrt{2}$ increase in a signal level. The antenna temperature is given by:

$$T_A = \frac{10^{-26} S}{2k} \left(\frac{\pi}{4} D^2\right) e \quad \text{(K)} \qquad (2)$$

where

S = total source flux density, jansky

k = Boltzman's constant (1.38×10^{-23} joule/deg)

e = antenna efficiency

D = antenna diameter, m

The factor of 2 in the denominator accounts for the fact that only single polarization of the power is received. With the inclusion of the factor and Eq. (2), we obtain an expression for the SNR per channel:

$$SNR_{ch} \doteq 2.05 \times 10^{-4} (\gamma_v S) D_1 D_2 \sqrt{\frac{e_1 e_2 BT}{T_{S,1} T_{S,2}}} \qquad (3)$$

The SNR/channel defined above is not to be confused with system SNR. With coherent addition of channels the system SNR available for detection is approximately equal to the above expression times N_{ch}, which is the number of channels coherently combined. However, for the ORION system, it is not the detection threshold that sets the lower limit on SNR, but the maximum allowed system-noise error in bandwidth synthesis (BWS) delay. If SNR_{ch} is approximately the same for all channels, the system-noise error in BWS delay is given by:

$$\sigma_\tau \approx \frac{1}{2\pi\, SNR_{ch} * \sqrt{\sum_k (f_k - \bar{f})^2}} \qquad (4)$$

where f_k represents the channel frequencies and f is the average of those frequencies.

The SNR lower limit arising from this expression can be approximately computed on the basis of the following assumptions. It is to be emphasized that the assumed quantities are not design goals but are set equal to "boundary values" in order to allow computation of a lower limit on SNR. First, assume that the maximum system-noise error in baseline length will not be allowed to exceed 20 percent of the total error budget of 2 cm. Second, for channel placement, assume the extreme configuration of seven channels at each edge of the 400-MHz passband at X-band. Under these assumptions, the minimum allowed channel SNR will be seven. If one places an even tighter requirement on system-noise error or assumes less extreme channel placement, the lower limit on channel SNR will be even greater. Thus, the ORION system will require channel SNR's of seven or greater. At this level, system SNR will be far greater than the detection threshold and detection will present no limitations.

The reader is referred to Ref. 5 for a detailed analysis of the SNR and other error sources involved in the ORION design. Also, Ref. 8 is an excellent bibliography of articles relating to VLBI.