THE CHALLENGE OF PROGRAMMED TRACKING LOW ORBIT SATELLITES FROM MOBILE GROUND STATIONS

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ABSTRACT

Orbiting satellites can be tracked by following preprogrammed ephemeris data in the ground station controller. This tracking method is advantageous, because of the reduced acquisition cost of non-autotracking receiver and antenna feed components. Further, widely separated frequency bands can readily be tracked, without the complexity of a frequency specific auto-track system.

Two types of mobile tracking systems are described. They are composed of elevation-over-azimuth-over-tilt and of an X-Y axis pedestal configuration.

The calibration methods for establishing time and geographical references are discussed, as well as the challenges of minimizing the effects of system and environment induced error contributors.

KEY WORDS

Non-autotrack; Program Track; Pointing Error; Mobile Ground Terminal;

INTRODUCTION

Traditional tracking of low orbit satellites was accomplished from a permanently installed ground station or from a pre-surveyed location. Most often an autotracking feed and receiver are are used for moving targets; but autotracking is a significant cost driver for such receive stations.

Late in the seventies Scientific Atlanta had built an L-Band meteorological receive terminal, attempting to provide a low-cost system with programmed track only. Technically it was successful, however, most customers did not opt for this approach, as they perceived it somewhat as a ‘blind faith’ performance promise.

Today the market has changed, and program-only receive terminals have proven themselves. Yet, the challenges are greater: X-Band and K_U-Band frequencies ask for higher pointing accuracies. The proliferation of remote sensing satellites, their wide spread utilization and the broad customer base bring about the need to make such ground stations transportable and even mobile - quickly deployable over roadways and by cargo airplanes.

Further complicating the matter, in some case widely separated bands, e.g. S-Band and X-Band, need to be combined in one terminal. An autotrack version of such an antenna feed is very expensive.

In order to circumvent the high cost of autotracking, and to permit the use of simultaneous and multiple receive bands, Scientific-Atlanta has developed a 6.1-meter three-axis and a 4.3-meter X-Y type antenna terminal. Both employ program tracking. At the same time they are built for mobility, which brings about an extra level of sophistication for calibrating the controller for varying geographical locations.

Such a receive terminal requires rigorous planning and design discipline in minimizing all of the tracking error contributors. The solution to this challenge is presented here.

DESCRIPTION OF AN X-BAND RECEIVE TERMINAL

Figure 1 depicts a simplified System Block Diagram of a 6.1 meter size antenna mobile receive terminal, typically used for remote sensing applications. It employs a three-axis tracking pedestal, which permits uninterrupted data reception and recording during overhead satellite passes. A tilt axis is used for this purpose under an elevation-over-azimuth pedestal, thereby moving the motion lock ‘keyhole’ away from zenith, i.e. the overhead satellite path.

A tilt sensor, mounted on the body of the elevation structure, is used to remove verticality errors. Those can be induced by quasi-static wind deflections, ground settling and non-level positioning by the tilt axis below, etc.

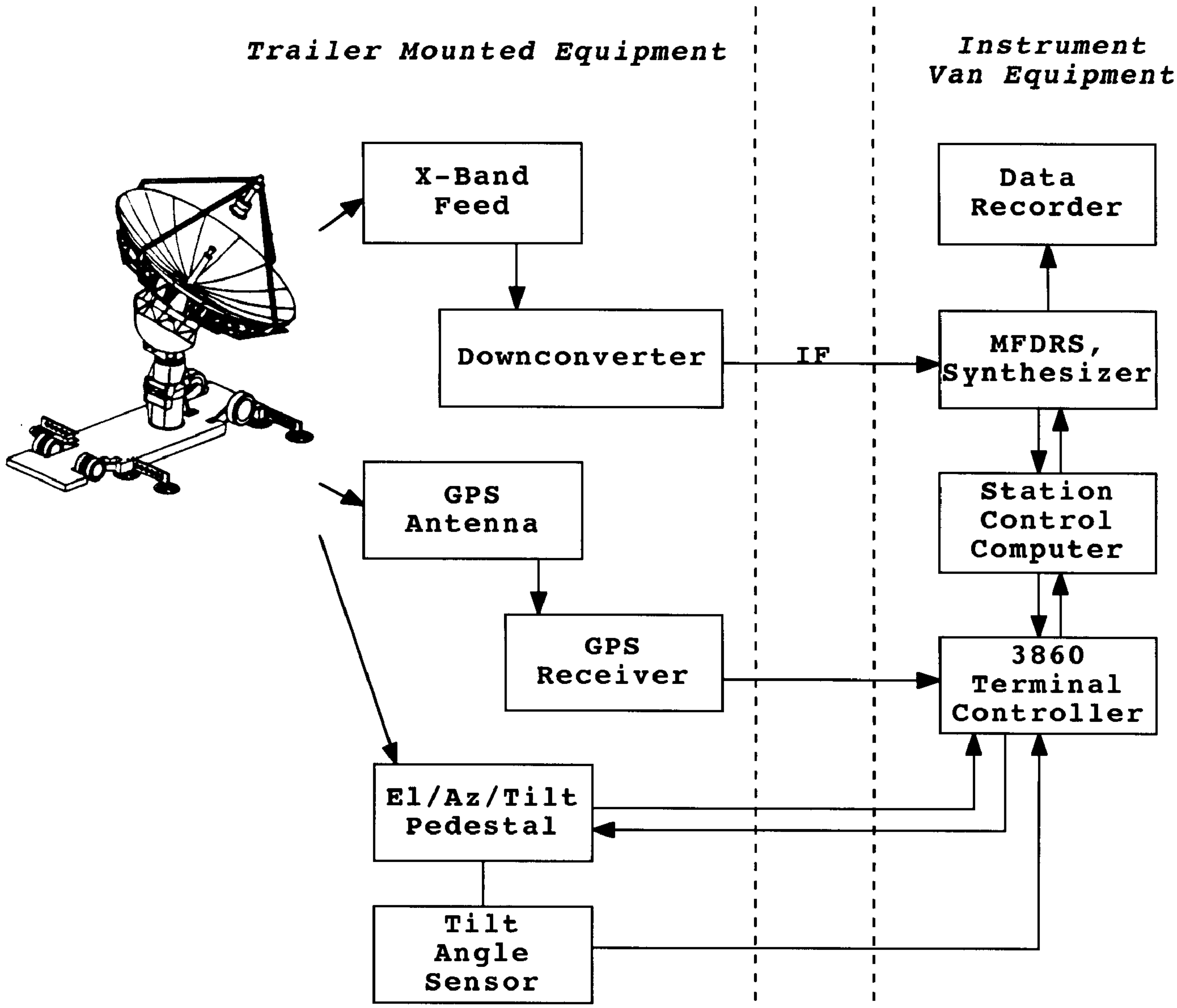

FIG. 1:
SIMPLIFIED SYSTEM BLOCK DIAGRAM
6.1 METER RECEIVE TERMINAL

The GPS receive subsystem is mounted to the reflector aperture. The function of this GPS receiver is to provide geographical position location and time reference. Furthermore, the primary axis of this 4-unit array of GPS antennas is accurately aligned with the pedestal motion axes. During a time span of roughly one hour it undergoes a self-calibration routine, after which the array primary axis orientation can be read. This angular read-out shows the position relative to North, and therewith an accurate pedestal coordinate system is established.

DISCUSSION ON ALLOCATING MAJOR SYSTEM ERROR CONTRIBUTORS

In order to visualize the implications of a design for program-only tracking of low orbiting satellite targets, refer to the illustration in Figure 2 - Coarse System Error Block Diagram.

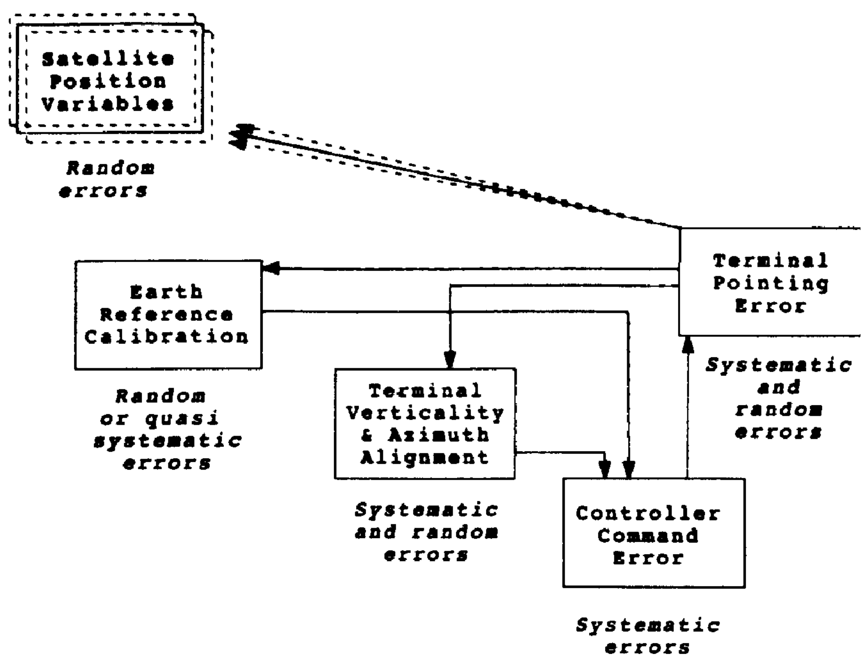

FIG. 2:
COARSE SYSTEM ERROR BLOCK DIAGRAM

The primary determinator for making the program track approach work is the permitted deviation by the ground receive antenna from its theoretical line-of-sight beam center. For example, we might permit a 0.5 dB reduction in signal strength under normal operating condition. For a 6.1 meter antenna at 8.4 GHz this translates to a beam deviation of about 0.17 degrees. This number must now be appropriated to the uncertainties particular to the satellite path prediction, the terminal's earth position calibration, the ground antenna pointing error and its control protocol. In this particular case the GPS reference system is mounted to the receive antenna; theoretically, some of the errors particular to the tracking antenna also influence the accuracy of the azimuth calibration. That is shown in the interdependency in the error block diagram. If another type of North reference calibration is used, like tracking of a celestial body, it can be subject to a sizable environmentally induced error from wind, etc.

The other variable, and quite often large error lies with the off-timing in the satellite orbit prediction.

Error characteristics of satellite orbit path prediction

Satellite ephemeris data is typically disseminated as elevation and azimuth position at a particular time, as seen from a point on earth. Low earth orbiting satellites are exposed to variable gravity vectors and also to frictional drag from gas molecules at the upper reaches of the atmosphere. This results in drift from the theoretically predicted orbit path of the satellite. Periodically, the satellite's on-board thrusters are commanded to compensate for this drift.

If the ephemeris data is relatively old, it may not include the latest path corrections. Often, however, it is the timing that is off by a few seconds, rather than the coordinates being incorrect.

Consider the orbit speed of about 0.07 degree per second of a low altitude satellite: at look angles near horizon this speed appears relatively at 0.025 degree per second at the ground station. Assuming three seconds uncertainty, this translates to a significant positional prediction error of 0.075 degrees or 45% of the total budget! It is therefore important to input fresh updates in the the ground station controller, before attempting a track.

A scanning acquisition routine is a helpful alternative, by using the measured timing error for immediate correction of the orbital elements. The above mentioned error of 0.075 degrees can therewith be removed. Of course, such a correction also diminishes somewhat the importance of always using the freshest ephemeral element data.

Error characteristics of geographical position determination

The ground station spatial reference to the satellite orbit shell includes altitude, longitude and latitude. The antenna pointing must also fix its azimuth Zero position angle relative to true North.

The approach used on Scientific Atlanta's 6.1 meter terminal employs Trimble's TANS VECTOR® GPS location system. Four individual antennas are mounted in a cross-fashion around the rim of the reflector antenna. The altitude, latitude, longitude and timing information is very accurate for the purpose of defining the geometric relationship of the satellite path and the earth location of the receive terminal. However, the center axis between two of the four antennas defines the azimuthal position. Add to this the uncertainty of this axis in relation to the pedestal azimuth Zero, and we have the error toward true North.

Using the GPS position location method has the advantage of being time, environment and geographically insensitive, i.e. an accurate fix can be made within an hour at any time during day or night at any place on earth. The price has to be paid in the cost of the equipment.

Other methods for determining North are available - with various restrictions and drawbacks:

- Magnetic reading: cannot be trusted to be better than 1 or 2 degrees. The local magnetic deviation information may not be available or may have changed, and cannot be used in far northern latitudes.

- Star calibration: this method can be very accurate, given the night optical equipment, sufficiently accurate RF-to-optical alignment and the right atmospheric conditions - and enough time! There are some spots on earth, where overcast skies persist for many weeks and even months. This certainly limits the universal usefulness of this type calibration.

- Sun and moon calibration: a tracking algorithm for these celestial bodies must take into account the relatively large target, but it can be done accurately with the proper mapping approach. Cloudy skies are no obstacle, however, at latitudes close to the South and North poles the sun or moon are hidden, often for very long durations. So, there are some geographical limits to using this approach.

ANTENNA TERMINAL ERROR ALLOCATION

Figure 3 outlines the sub-elements and structures, which constitute the mobile tracking pedestal and antenna. The error block diagram shows the influence and interrelation of various alignment, static and dynamic error contributors. The three-axis configuration of elevation-over-azimuth-over-tilt applies to Scientific Atlanta's 6.1 meter terminal. For converting this diagram for the 4.3 meter two-axis X-Y system the upper two axes can be renamed, and the tilt axis portion be removed.

In designing for an overall tight pointing error it is important to realize the importance of making the load path through the trailer bed, the jacking mechanism and the ground pad interface with the ground as rigid as possible.

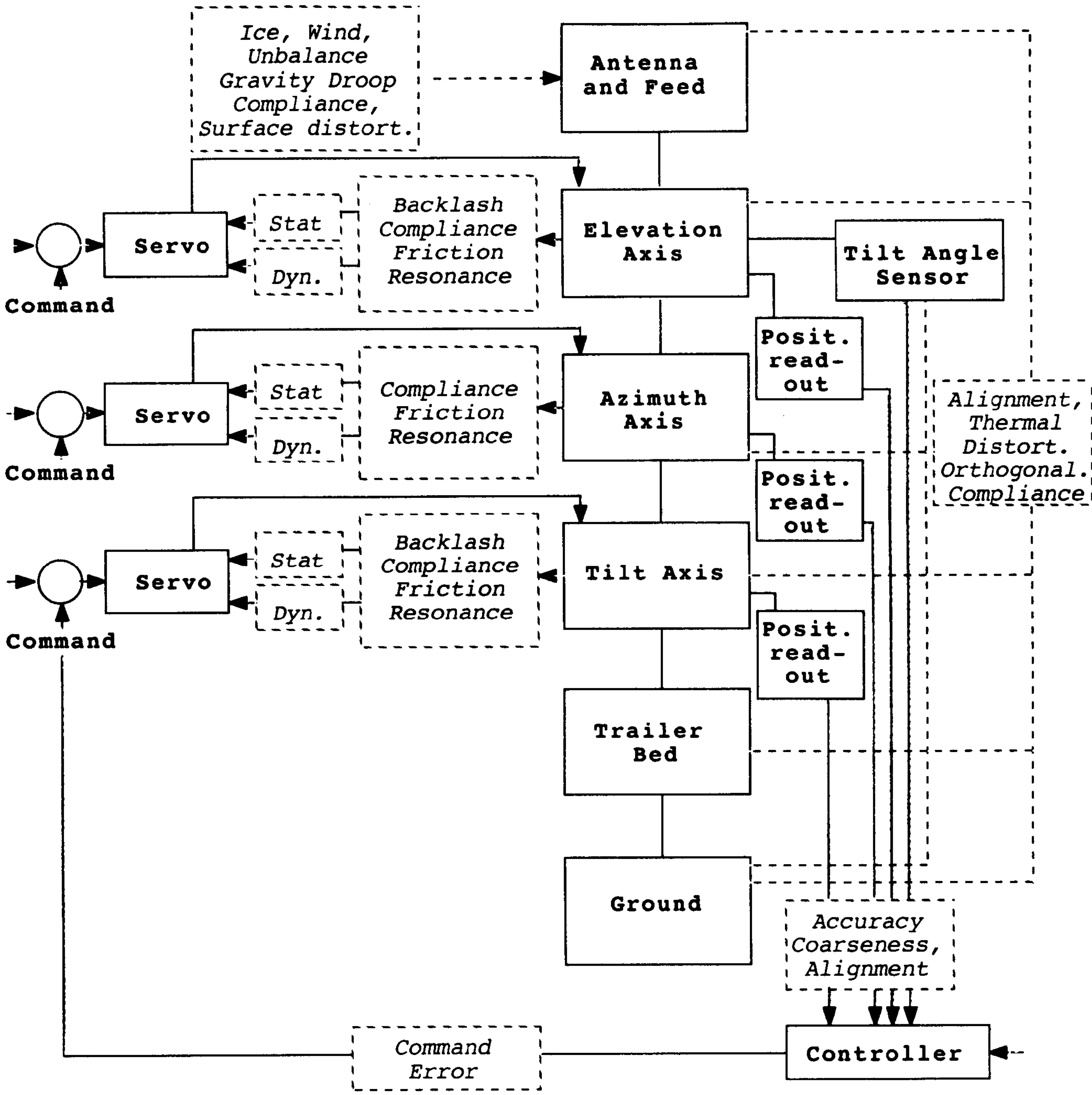

FIG. 3:
TERMINAL ERROR BLOCK DIAGRAM

Table 4 shows the error budget for the tracking terminal. The individual errors are calculated and measured values for the 6.1 meter receive terminal. The tabulation includes systematic and random errors at various elevation angles. Wind induced values are for 70 km/h steady state, with a typical gusting spectrum. As can be seen from the results, the summary errors for the terminal are less than 0. 12 degrees RMS, and fit well within the overall budget of 0. 17 degrees.

DESCRIPTION OF THE 6.1 METER TRACKING TERMINAL

Photograph No. 1 shows the deployed antenna terminal. The design utilizes a special trailer, which permits complete retraction of its wheels. This has two major advantages: one, the space atop the trailer bed can be utilized to the fullest, in that the height inside C-130 and C-141 cargo aircraft is limited to 2590 mm. The roll-on / roll-off method for the loaded trailer allows it to move in and out of the aircraft with just a small amount of clearance toward the cargo floor. Two, during operation the trailer 'squatting' close to the ground maximizes the structural stiffness, and minimizes the antenna height above ground. Therefore also the wind induced moment loads - and therewith the errors - are held to a minimum.

Note that the terminal is deployed autonomously. No auxiliary handling or lifting devices are needed for set-up and take-down.

DESCRIPTION OF THE 4.3 METER TRACKING TERMINAL

Figure 4 depicts the 4.3 meter tracking terminal in operation. It uses an X-Y antenna mount, which has much commonality with Scientific Atlanta's 3 meter IRIDIUM®™ terminal. The latter is also used for precision program-only tracking at the 20 to 30 GHz frequency band. Similar to the 6.1 meter system, the 4.3 meter terminal is making optimal use of the space above the trailer deck for minimum transport height. Additionally, the center part of the reflector and the spars with feed remain always mounted, assuring accurate system erection, without recalibration or special alignment. The spars remain in a folded position, while the pedestal is transported horizontally.

The X-Y axis configuration of the pedestal is ideally suited for applications of tracking overhead satellite targets, without the complexity and high acceleration and velocities of a tilt mounted elevation-over-azimuth pedestal. The X-Y axis configuration effectively relocates the motion lock keyhole of an El-Az mount from Zenith to Horizon. If the trailer is oriented such that the keyhole is oriented roughly to East/West, then all North/South satellite orbit paths can be tracked very smoothly.

Table 4:

Pointing/Tracking Error Budget Summary (Worst Case)						
	Elevation Angle (Degrees)					
	0		20		60	
	EL	AZ	EL	AZ	EL	AZ
Bias (Fixed) Errors* Coordinate Axis Alignment	0.0165	0.06	0.0165	0.056	0.0165	0.03
Orthogonality	0	0	0	0.0020	0	0.0052
Collimation	0.01	0.01	0.01	0.01	0.01	0.01
Structural Deformation (Gravity)	0.037	0	0.035	0	0.0185	0
Servo Amplifier Drift and Offset	0.007	0.007	0.007	0.007	0.007	0.004
ε_{bias} (RMS) = 1/3 [$\Sigma\ \varepsilon$ (peak)]	0.0235	0.0257	0.0228	0.0250	0.0173	0.0164
Random Errors** A. Static Error Gear Backlash	0 .01	0	0 .01	0	0.01	0
Structural Deformation (Wind)	0	0.0267	0.0133	0.025	0.0267	0.0133
Structural Deformation (Thermal)	0 .01	0	0.01	0	0.01	0
Resolver Readout	0.01	0.01	0.01	0.01	0.01	0.01
Wind Torque (Gust)***	0	0.021	0.011	0.021	0.021	0.021
Program/Steptrack	0.05	0.05	0.05	0.05	0.05	0.05
ε_{RS} = $[\Sigma\ \varepsilon_i^2\ (RMS)]^{1/2}$	0.0523	0.0613	0.0557	0.0605	0.0629	0.0567
Static Pointing Error ε_{static} (RSS) = $[\varepsilon^2_{bias} + \varepsilon_{RS}^2]^{1/2}$	0.0579	0.0665	0.0601	0.0655	0.0652	0.0590
B. Dynamic (Target-Related) Errors Velocity Lag (K_V)****	0.01	0.01	0.01	0.01	0.01	0.005
Acceleration Lag (K_A)*****	0.05	0.05	0.05	0.05	0.05	0.05
$\varepsilon_{dynamic}$ (RSS) = $[\Sigma\ \varepsilon_i^2\ (RMS)]^{1/2}$	0.051	0.051	0.051	0.051	0.051	0.0502
Total Error Per Axis (RSS) ε_{axis} (RSS) = $[\varepsilon^2_{static} + \varepsilon^2_{dynamic}]^{1/2}$	0.0772	0.0838	0.0789	0.083	0.0828	0.0775
Total System Error (RSS) $\varepsilon_{sys} = [\varepsilon^2_{AZ} + \varepsilon^2_{EL}]$	0.1139		0.1145		0.1134	

* All bias errors are peak errors. The RMS bias error contribution for the worst case is calculated adding the peak errors algebraically.

** Random errors assume a normal distribution. Therefore, the RMS error is equal to one-third the peak error.

*** Wind torque error computed for 70 km/hour, wind gusting to 95 km/hour.

**** Velocity lag computed for 2 deg/sec velocity.

***** Acceleration lag computed for 0.5 deg/sec^2 acceleration.

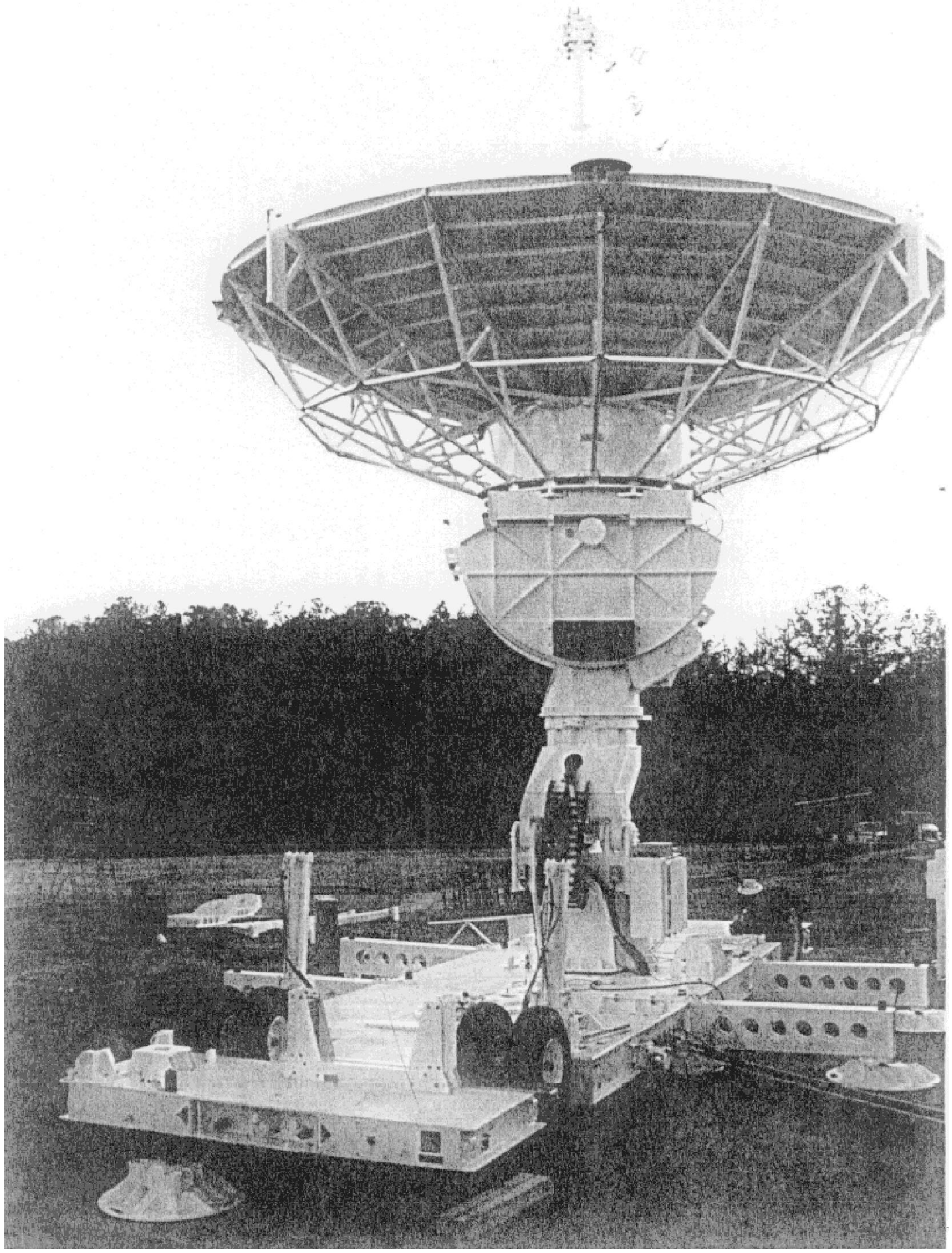

Photo
No. 1

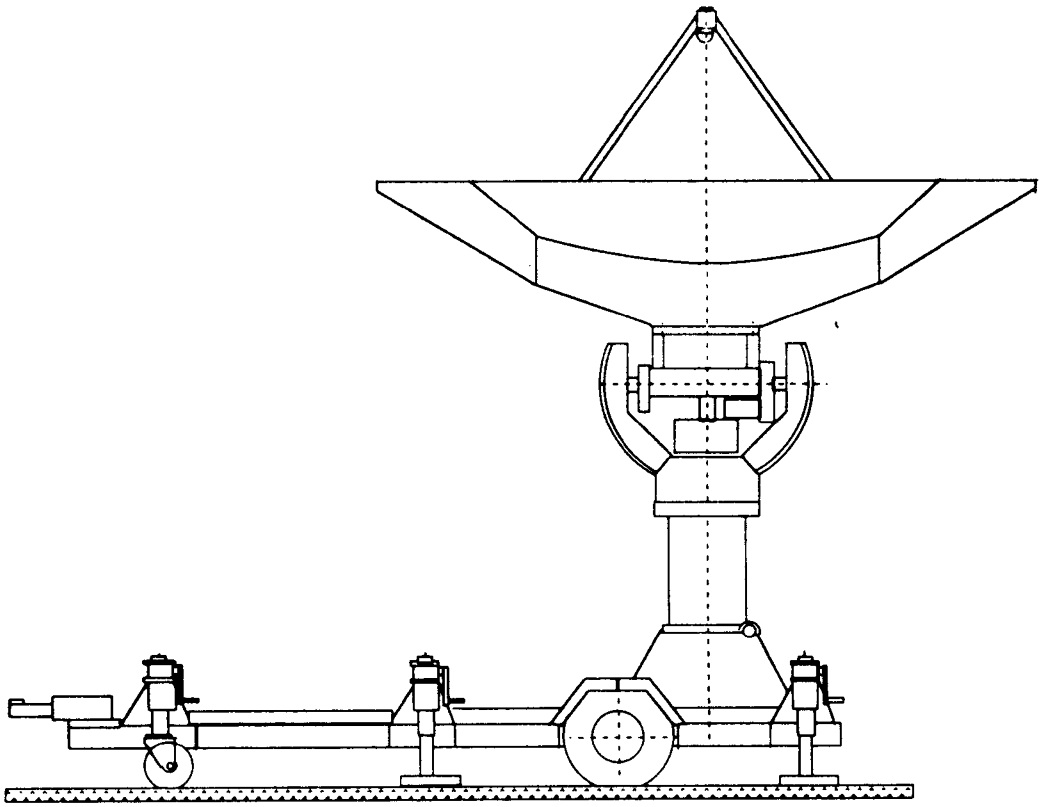

FIG. 4: 4.3-METER X-Y MOBILE RECEIVE TERMINAL

CONCLUSION

It is necessary to apply rigorous planning and design discipline in constructing a large, precision antenna terminal for program-only satellite tracking use for flexible worldwide deployment. The limits of this tracking method must be recognized and the error contributors be properly budgeted. The result can be a relatively low cost system, which meets high performance expectations. Scientific-Atlanta has successfully met this challenge in the design of its mobile antenna terminals.