1994

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AIAA 94-4688, AIAA Space Programs and Technologies Conference, September 27-29, 1994, Huntsville, AL.

https://hdl.handle.net/10945/34482

AIAA 94-4688

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AIAA-94-4688

TOPAZ II NUCLEAR POWERED SAR SATELLITE

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Abstract

The AA4871 Spacecraft Design course is the capstone class for the M.S. in Astronautics at the Naval Postgraduate School. The design team integrated a Topaz II nuclear power system with an EOS Synthetic Aperture Radar to design a low Earth orbit, three axis stabilized satellite flying in a gravity gradient stable orientation. The SAR is a high resolution, electronically steerable, Earth science data collector for glaciology, hydrology, vegetation, oceanography and geology which penetrates clouds, foliage and shallow soil layers. The antenna modules provide global, regional, and local high resolution mapping. Tradeoffs were analyzed to optimize coverage, satisfy nuclear safety issues, and to satisfy defined revisit and resolution requirements. The design emphasized use of qualified and readily available components and subsystems. The satellite features a cylindrical monocoque aluminum structure, and a sun synchronous orbit simplifying thermal control design. It has a momentum bias attitude control system with momentum wheels and thrusters. The antenna has microstrip radiating elements on a honeycomb metal and composite structure and is articulated with respect to the spacecraft via an electric gimbal motor. Existing satellite control and data processing and distribution facilities and an existing launch vehicle and launch site limit cost and technical risk.

I. Introduction

The integration of the Topaz II reactor and the EOS SAR for scientific purposes was explored by another Naval Postgraduate school design team. This team's approach featured a design whose major axis is oriented in the direction of the velocity vector and a fixed SAR antenna. Both features are among those that are significantly different from the design discussed in this paper. This paper is brief summary of the major design considerations in developing the TOPAZ II Nuclear powered SAR Satellite.

II. Discussion

System level requirements

In general, the system level requirements can be classified into two distinct categories; science requirements and system requirements.[1]

The science requirements are to collect data that will provide information on; glaciology, hydrology, vegetation science, oceanography, and geology. By operating at three frequencies and various polarizations the EOS SAR will satisfy these requirements. Coverage and resolution requirements will be provided by multi-mode operation. The SAR will have the capability to operate in three different modes; global operating, regional mapping, and local high resolution with the latter having the smallest swath width. Resolution will increase with the corresponding decrease in swath width. A revisit time of 3 days is required for glaciology studies and some hydrology studies. To ensure timely data delivery to the user the TDRSS system will be used. The two channel TDRSS satellite to satellite data-link system is capable of a 150 Mbps transfer rate per channel.

The SAR is the primary sensor for this mission. It is based on the EOS SAR as described in the RFP and in the SAR Earth Observing System Instrument Panel Report, executive Summary (NASA, EOS SAR, Volume IIf, 1992). The antenna will be articulated to allow viewing free from satellite interference. The satellite system will be powered by the TOPAZ II nuclear power system as described in the RFP and in the NEP Executive Summary (NEP Space Test Program Preliminary Nuclear Safety Assessment, November 1992). The power system requires that the satellite operate from a nuclear safe orbit with a lifetime of 600 [2] years. Mission life is three years. All mission operations will be

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provided by an operations center at Goddard Space Flight Center. This shall include all data processing functions and distribution. Launch into a sun-synchronous orbit will take place from Vandenburg AFB aboard an Atlas IIAS/Centaur rocket.

Configuration

The configuration consists of five major components: the TOPAZ II reactor, the telescoping reactor boom, the main bus, the SAR antenna arm, and the SAR antenna (Figures 2,3,4). The primary driver for the configuration was the need for shielding the SAR antenna and main bus from the harmful radiation emitted from the reactor. Additionally, design consideration was given to payload requirements, thermal control, and launch vehicle limitations.

Mission Requirements The main requirement for the configuration is to integrate the subsystems into an effective design that meets or exceeds the requirements listed in the RFP. Five major considerations drove the design. First, the need to provide a stable platform for the SAR antenna. Second, the requirement to separate the reactor from the main bus for thermal as well as radiation protection. Third, the design had to conform to size, mass, and center of mass constraints imposed by the ATLAS IIAS launch vehicle. Fourth, the design had to ensure adequate accessibility to components contained within the main bus. And fifth, the requirement to provide adequate thermal control of the spacecraft during all phases of operation.

Design Tradeoffs Because the reactor needs to be separated from the spacecraft bus, the configuration resembles a dumbbell with large moments of inertia perpendicular to the long access and a much smaller one parallel to it. This configuration, when oriented perpendicular to the orbit, is ideal for exploiting the benefits of gravity gradient stability. The challenge with this attitude is that the 8 degree half angle cone of shielding provided by the TOPAZ II reactor is inadequate to cover the 20 meter SAR antenna unless separated by a distance of approximately 72 meters. While orientation in a gravity gradient unstable attitude alleviates the shielding problem, there are increased attitude control and antenna pointing problems. After discussions with TOPAZ II experts, the decision was made to increase reactor shielding and utilize the gravity gradient stable orientation. This will provide the required shielding for the SAR antenna without the prohibitively long separation between it and the reactor. To save mass, the shield is wing shaped, providing coverage along the length of the SAR antenna and for 30 degrees of antenna yaw.

With the satellite oriented in a gravity gradient stable attitude, the decision was made to make the antenna gimbaled about two axes instead of rotating the entire spacecraft with the antenna fixed. Using an arm and gimbal system, the antenna will be deployed centered under the main bus. SAR antenna pointing requirements call for 30 degrees rotation in yaw and 30 degrees rotation in roll with respect to the spacecraft. Additionally, a 90 degree pivot is required for stowage. A tradeoff between center and side suspension was conducted. For center of mass considerations, center suspension is preferred. But launch vehicle interface proved to be difficult due to the need to have a portion of the arm pass through the launch vehicle interface. This would have required a custom interface. In order to reduce costs and increase reliability, customization was discouraged in favor of off-the-shelf components wherever possible. Hence the decision to use side suspension and counter the adverse center of mass due to the SAR arm with smart component placement within the bus. The 2.2 meter arm will be attached to the bus by a truss assembly attached to the thrust cone. SAR antenna pointing will be accomplished by a motorized gimbal placed at the end of the antenna arm. The antenna will be connected to the gimbal by a clamshell hinge assembly that facilitates antenna stowage.

The size of the SAR antenna (20x4 meters) requires that it be folded in order to fit inside the fairing of the ATLAS IIAS. Consideration was given to both internal and external stowage designs. The internal design provided a means to achieve center antenna suspension without launch vehicle interface problems. That is, without having the SAR antenna support pass through the launch vehicle adapter; the arm would simply deploy down through and out the central cylinder and cone. But that design required numerous folds as well as a larger buss size. The external stowage design does not allow for center suspension without the launch vehicle interface problems discussed above. However, external stowage offers the advantage of fewer folds combined with thermal protection to the bus during the unheated coast phase. For these reasons the external stowage configuration was chosen.

System Description The TOPAZ II provides the primary electrical power for the spacecraft. It is 3.9 meters long and with the added shielding will have a mass of approximately 1757 kg. The reactor shield provides 8 degree half angle cone of radiation protection. The additional shielding will provide a 27 degree half angle along the length of the SAR antenna. The additional shielding is shown in Figure 1 below.

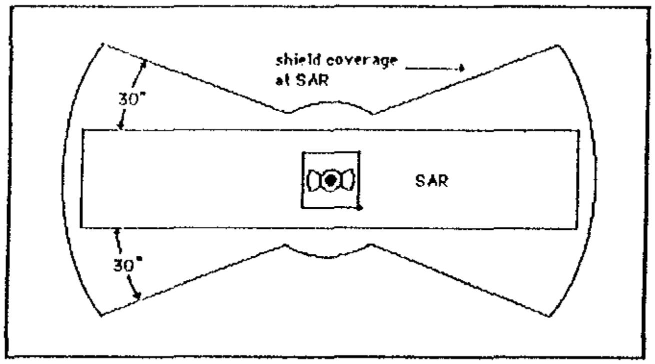

Figure 1. Reactor Shield Coverage.

Separation is required to adequately protect the spacecraft bus from harmful radiation of the reactor. To accomplish this, the reactor is connected to the main bus by an extendible telescopic boom assembly. The boom will be acquired from the Astro Aerospace Co. of Santa Barbara and be based on their design for EOS SAR. The self contained boom system will be recessed by one meter into the top cylinder of the spacecraft structure. When fully deployed, the boom will provide 11.8 meters of separation between the radiation shield and the bus. This is adequate for the protection of the main bus electronics. The boom will have 16 segments 0.80m long with top and bottom diameters of 0.20m and 0.60m respectively. The two segments closest to the reactor will be constructed of stainless steel to resist the high temperatures generated by the reactor. The remaining sections will be fabricated out of aluminum. Boom deployment nominally takes 15 minutes. Electrical power cables are draped from the sides of the segments prior to deployment and released as the boom extends. The whole system has a mass of approximately 80 kg.

The main bus consists of a top cylinder, a central cylinder, a cylinder cone, eight support panels, and support struts and trusses. It supports and provides thermal protection for all the electronics associated with the satellite. In addition it provides a mounting platform for the TT&C and omni antennas. A single propellant tank will be located inside the cylinder cone and will be capable of holding 295 kg's of hydrazine fuel.

The SAR antenna arm attaches to the main bus by a truss that is connected to the cylinder cone. The arm is hinged at the truss and again at the end of the 2.2m arm. Attached to this top hinge is the gimbal which provides the antenna pointing. The arm has a mass of 20 kg and the gimbal a mass of 15 kg.

The SAR antenna is the largest single component on the spacecraft. It has a length of 20 meters, a width of 4 meters, and a thickness of 5.2 cm, and a total mass of 1130 kg. It is connected to the gimbal through a clamshell hinge mechanism. The SAR is hinged into eight panels of lengths 2.7m, 2.5m, 2.6m, 2.0m, respectively from each direction of the gimbal. The hinges are spring loaded to aid in deployment and damped to protect against over stressing. In its stowed configuration, the antenna is restrained by struts connected to the main bus by explosive connectors. The connectors are controlled through the Command, Timing, and Telemetry unit to sequence antenna deployment.

The SAR antenna will be deployed following completion of the reactor boom deployment. Timing signals from the Command Timing and Telemetry (CT&T) computer will sequence the deployment by first fully deploying the four panels on one side of the antenna. With that side deployed, signals will be sent to deploy the other side. With both sides deployed, the arm will deploy and lock into its operational position.

Budgets Budgets for mass, power, and propulsion were developed. The maximum power requirement is for 4433 W during peak operation. The propellant needed for the mission came to 295 kgs. The mass budget is shown in Table 1. The dry spacecraft weight was calculated using only the mass of the components that were not off-the-shelf. The mass of the SAR antenna and its associated electronics were determined to be 1130 kg and 413 kg respectively. Total spacecraft separation mass is 5168 kg leaving a 32 kg launch mass margin over and above the 15% mass margin of developmental items.

Panel Layout There are total of eight panels which provide structural stiffness and mounting support for subsystem components. The location of the subsystem components was determined by an iterative process that included: mass required for support systems, center of mass location, thermal control, and component accessibility. Highest weighting was given to total mass due to launch vehicle constraints. The center of mass of the spacecraft had to be within 0.10m of launch vehicle centerline and within 4.10m of the adapter. For thermal control, components that dissipated the most power were placed on the anti-sun side of the bus. Component accessibility is assured by the use of swing away panels that will allow easy access to subsystem components prior to SAR antenna attachment.

Moments of Inertia Moments of inertia were calculated from contributions of individual components and tabulated on a spreadsheet. All components were assumed to be of simple shapes and constant density. Calculations were done for both stowed and deployed configurations. The difference in beginning of life and end of life moments of inertia were negligible.

SAR Antenna

The payload of the spacecraft is a synthetic aperture radar (SAR) designed to meet the requirements set forth in the RFP. This instrument is to be based on the design of the Earth Observing System (EOS) SAR with minimum modifications. Besides the deployable antenna, the payload includes all associated SAR electronic support equipment. To reduce development costs and time, existing technologies and facilities will be used as much as possible. The science and data requirements for the SAR on this mission are based on the EOS SAR mission requirements.

Performance Requirements The science requirements are to collect data that will provide information on glaciology, hydrology, vegetation science, oceanography, and geology. The EOS SAR was selected to fill these requirements. It operates at three frequencies (L-, C-, and X- bands) with multipolarization. The three operating modes of the SAR would provide the required resolution and coverage (global mapping, regional mapping, and local high resolution mode).

Design Tradeoffs Altitude is the most important design criteria for any spaceborne radar. Lower altitude means finer resolution, improved power consumption, and reduced noise levels. While the preferences of the primary instrument drive the altitude selection in most design projects, for this satellite other design considerations were judged equally important. The safe altitude requirements of the TOPAZ II nuclear power supply and the revisit interval of the EOS mission led to the altitudes selected. For SAR calculations, a nominal altitude of 1005 kilometers was used. This high altitude reduced the useable incident angles for the SAR due to increased power and noise levels of the instrument.

The RFP requires the design of the antenna be based on the EOS SAR design with a minimum of modifications. Figure 5-1 illustrates the basic design flow of a SAR antenna (Elachi, 1988, pp. 109-112). The boxed parameters are inputs to the design from the EOS antenna. The width of the SAR is the sum of the L/C/X-band antenna widths. This is determined from where PRF is the nominal pulse repetition frequency of the antenna. This initially created a wide antenna that was beyond the size of the launch vehicle's shroud. By reducing the operating PRF range a smaller antenna width was found. The next step requires resolving ambiguities from "ghosts" or "aliasing" which occurs when the PRF is not high enough to satisfy the Nyquist sampling criterion. These ambiguities produce noise which can be reduced by maintaining a minimum size antenna area. The minimum area equation combined with the maximum width equation resulted in the antenna length. The proportional effect of incident angle is significant. The earth's horizon is at 59° incident angle, achieved with an antenna look angle of 48.5°. This incidence angle creates a prohibitively large antenna width and length. Reducing this useable incident angle to 55° (look angle of 45.2°) brings a corresponding reduction in size and also reduces required transmitted power in later calculations. Increasing PRF improved signal to noise ratios with its corresponding increase in average power, but increased the antenna width.

Tradeoffs in the antenna maneuvering method were also considered. The antenna will be physically pointed at a 30° look angle, with its electronic beam steering capability (± 23° available, ±16° required) easily providing incident angle coverage from 15° to the maximum of 55° (the lower limit is related to basic SAR principles [Elachi, 1988]). Electrical motors and gimbals on the antenna boom will roll the antenna to the other side of track and yaw the antenna to perform any required squint maneuvers. Since most time will be spent with the antenna looking cross-track, an efficient technique for performing the occasional squint maneuver was required. The performance of the electric motors was compared to yawing the entire spacecraft; with the motor being selected for its improved accuracy, simplicity, and decreased propellant usage. In the end, the increased weight of shielding from the reactor flux reduced the yaw angle to 30°.

Antenna Pointing Accuracy The electrically gimballed motors will point the antenna with an accuracy of 0.10° in either roll or yaw directions. The pointing accuracy or stability of the spacecraft platform is set to 0.25°. Total error in any direction should be less than 0.5°, which is the maximum amount that can be easily compensated for in the processor (Elachi, 1988, pp. 103-106).

System Design Description The EOS SAR has inherited most of its technology from the Shuttle Imaging Radar, Version-C (NASA, EOS SAR, Vol. IIf, 1992). The SIR-C is an L/C-Band antenna utilizing a uniform grid of dual-polarized microstrip antenna elements with separate polarization port feeds. Each frequency and polarization port is fed a separate receiver and data channel which allows capture of the amplitude, phase, and polarization of the antenna echoes. This antenna will also use the distributed SAR technology. It positions the transmit/receive modules behind the radiating elements to avoid power losses and significantly increase efficiency with a corresponding improvement in receiver sensitivity (Ball Communications System Division, 1992). It should be noted that the antenna is relatively thin at just 5.2 cm in thickness. The nomex honeycomb and metal matrix composite backplane provide the structural stiffness with the honeycomb also resisting thermal warpage. This unique structure and the electronic distribution system allows the antenna to be folded on itself for launch. The overall dimensions of the antenna are 4.00 m by 19.6 m. This allows for a 2.92 m wide L-band array, a 70 cm wide C-band array, and a 38 cm wide X-band array.

The antenna array is configured with its very efficient (75%) transmit/receive modules connected to the microstrip subarray elements along the elevation axis of the antenna. This allows the phase shifters to electronically steer the beam in the cross-track direction. Estimated peak radiated power is 3.0 kW, 3.6 kW, and 5.0 kW for L-, C-, and X-band, respectively. Total operating power required for the antenna is 650 W with all three bands transmitting at the maximum look angle (45°).

A breakdown of the individual antenna components mass is derived from a white paper by Ball Aerospace Systems Group. The total antenna mass is 1130 kg, with a density of 14.4 kg/m^2. This compares favorably to current and anticipated SAR designs of 10.8-15.5 kg/m^2.

A summary of SAR antenna design considerations is presented as Figure 5.

Support Equipment The support equipment for the Topaz II SAR is derived from the current system of the SIR-C and the projected design of EOS SAR. The support equipment for the SIR-C includes limited integration and size/mass reductions.

Masses for electrical and mechanical integration have been incorporated into each component. The efficiency of each item is 15% (similar to the current SIR-C system) resulting in 85% of electrical power used being rejected as heat.

Performance The overall performance of the SAR antenna is summarized in Table 2 with a comparison to EOS SAR included. Differences between the two include the squint angle (reduced for shielding weight), incident angle (reduced due to altitude and transmitted power considerations), PRF (adjusted for antenna width and peak power limits), peak power (reduced in L-band since adequate resolution and SNR achieved at lower power), resolution (improved due to narrower beamwidth), and swath width (improved due to increased altitude).

It has previously been determined that with the radiating surface in sunlight and the electronics surface dark, the end-to-end single arch bending of the antenna would degrade performance 20-40%, with X-band being the most severely affected (Ball Communications System Division, 1992). Further study of this issue is warranted since increasing thermal warpage resistance would bring a corresponding increase in mass.

References

1) RFP AIAA/Lockheed Graduate Team Space Design Competition and Supplemental Data Package, Preliminary Release, AIAA, Washington, D.C., April 15, 1993.

2) Bowden, B., Buesking, D., Cuff, D., Feuerstein, M., Gardner, P., Nicholson, J., Patterson, S., Rewald, S., Snaza, C., Tyler, C., Victor, E., "TOPAZ II Nuclear Powered SAR Satellite", Naval Postgraduate School, 25 March, 1994.

3) Elachi, C., Spaceborne Radar Remote Sensing: Applications and Techniques, IEEE, New York, 1988.

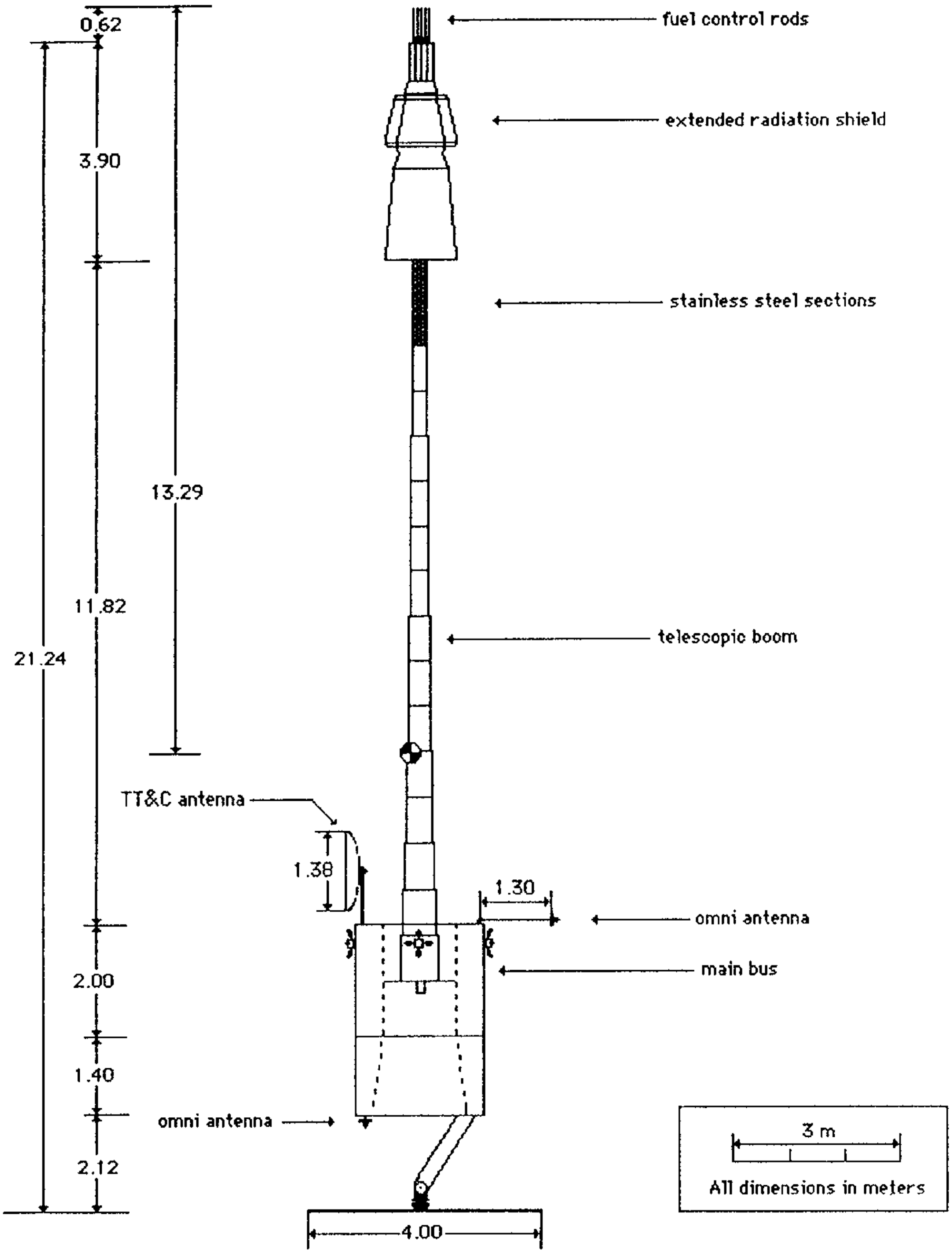

Figure 2. Head On View.

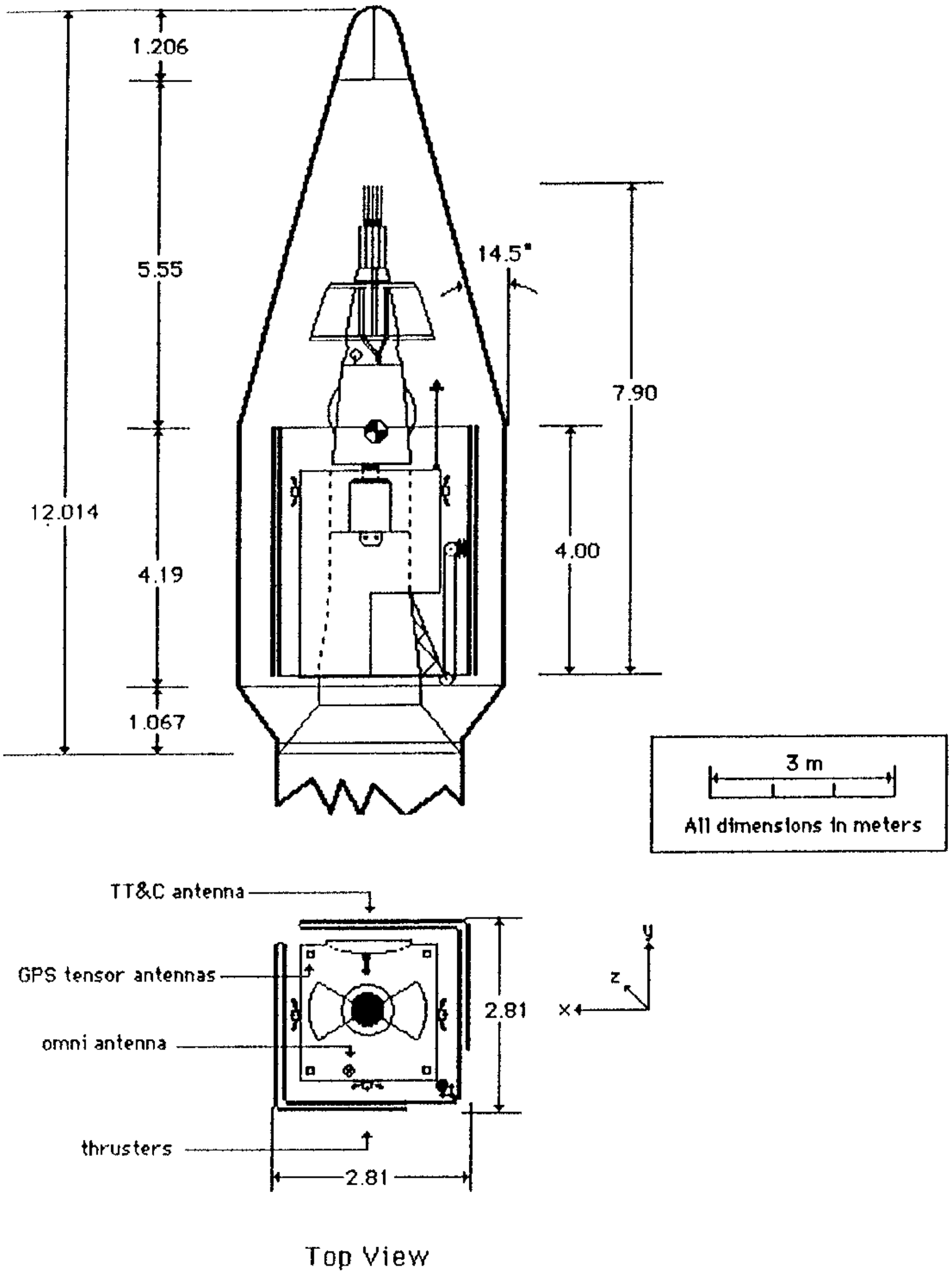

Figure 3. Stowed Configuration.

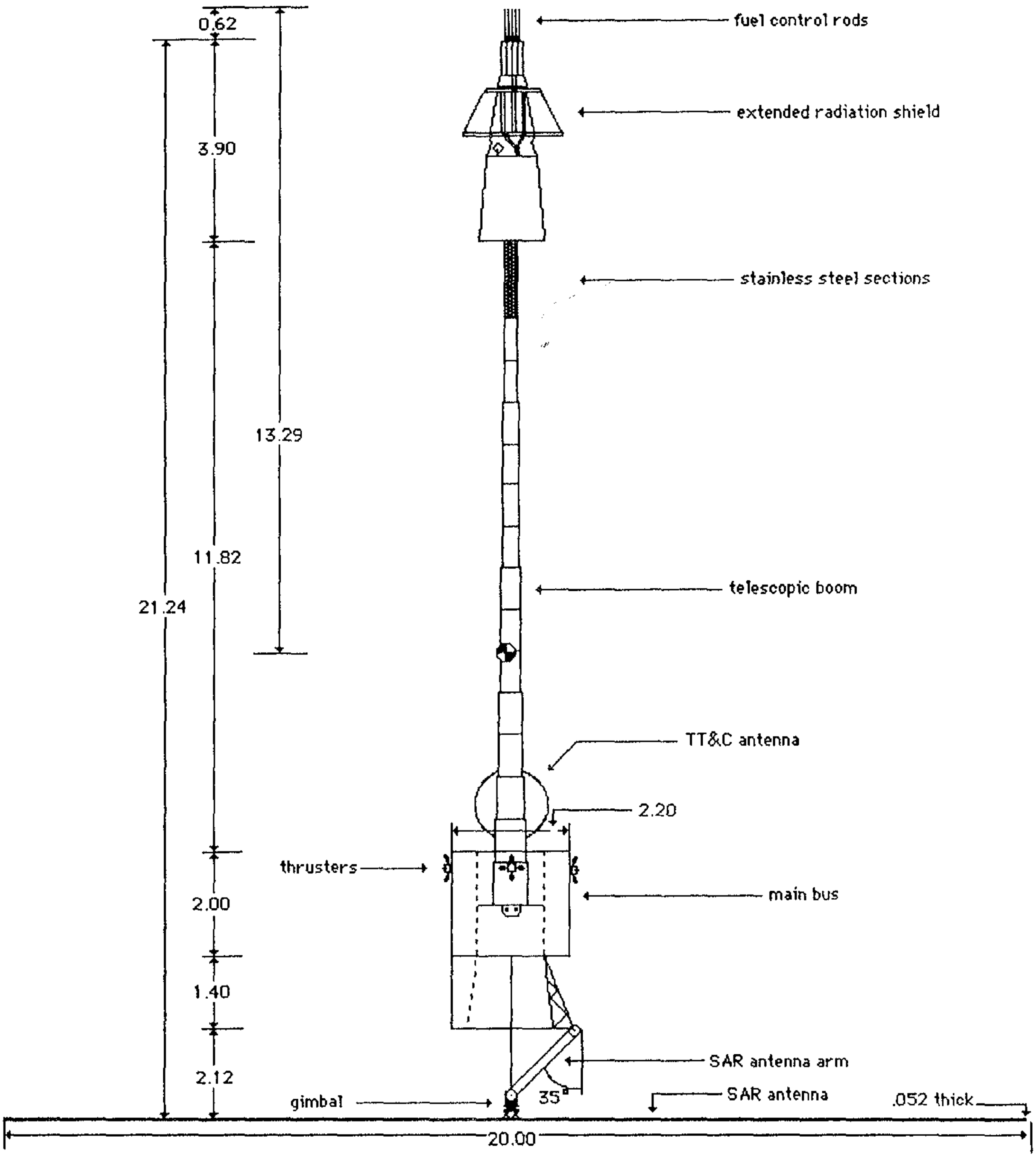

Figure 4. Side View.

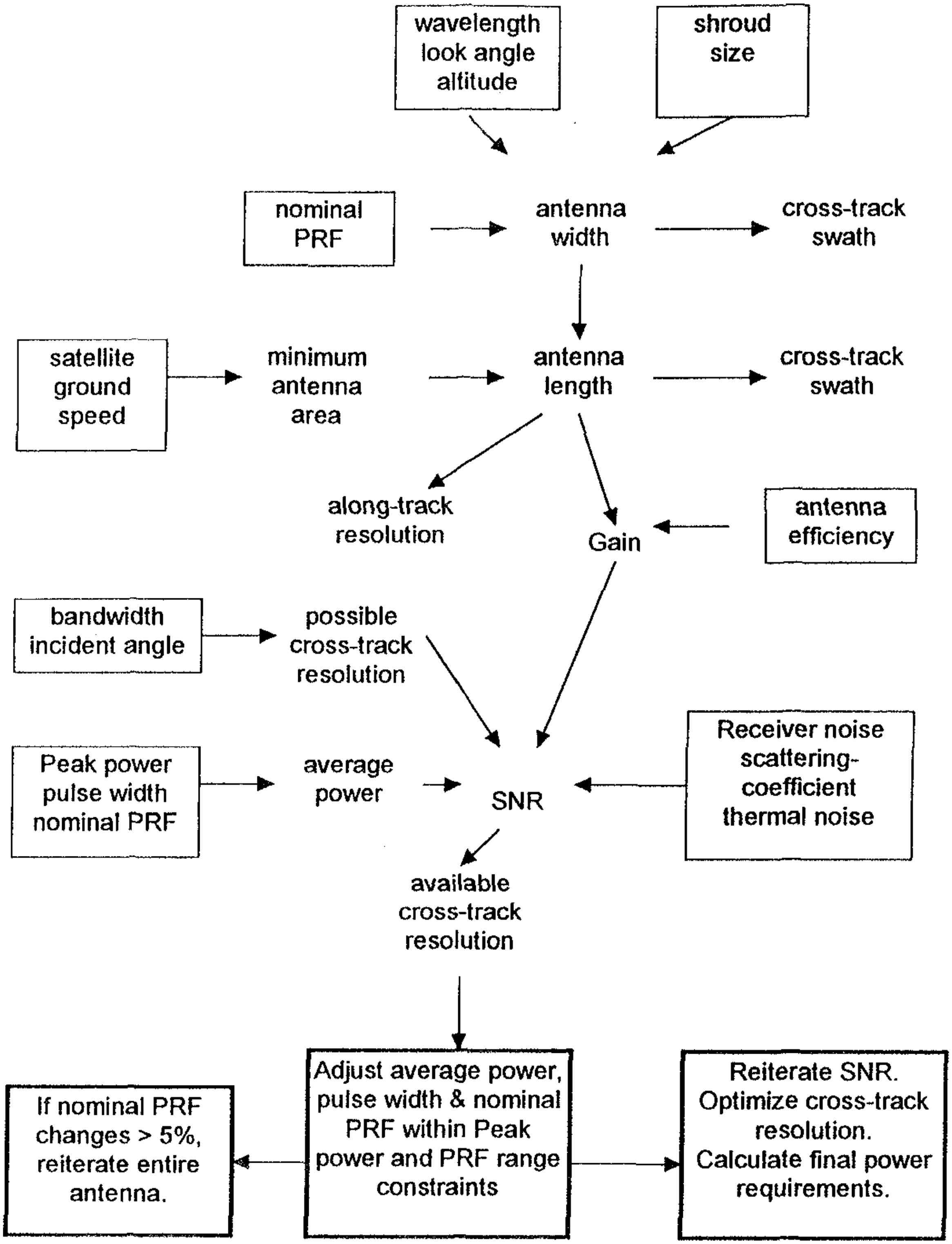

Figure 5. SAR Antenna Design Flow Diagram.

Table 1. Mass Budget.

SUBSYSTEM	**Mass (kg)**
Payload; Antenna	1130
Payload; Electronics	413
Structure #	484
TT&C #	281
Propulsion #	156
Attitude Control #	95
Thermal Control #	100
Electrical Power Gen./Dis.; Reactor	1180
Electrical Power Gen./Dis.; Shield #	546
Reactor Boom	80
Antenna Arm #	35
Electrical Integration	74
Mechanical Integration	45
Mass Margin (15% of # Components)	254
Dry Spacecraft Mass	4500
Propellant	295
Spacecraft Mass at Separation	**5168**

Table 2. SAR Performance Summary.

System Parameter	EOS (L/C/X Band)	TOPAZ II
Look Angle	15°-60°, left/right	15°-45°, left/right
Squint Angle	0°-60°, forward/back	0°-30°, forward/back
Incident Angle	15°-65°	15°-55°
Wavelength	23.9, 5.7, 3.1 cm	23.9, 5.7, 3.1 cm
Polarization	Quad/Quad/Dual	Quad/Quad/Dual
Pulse Width, PRF	50 µsec, 750-1100 pps	50 µsec, 750-1000 pps
Bandwidth	20, 10, 5 MHz	20, 10, 5 MHz
Peak Power	6.0, 3.6, 5.0 kW	3.0, 3.6, 5.0 kW
Resolution	20-500 m	15-400 m
Swath	30-700 km	80-1100 km