The HYDROS Mission: Requirements and Baseline System Design[1,2]

Eni Njoku, Michael Spencer, Kyle McDonald, Joel Smith
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109, USA
818-354-3693, eni.g.njoku@jpl.nasa.gov

Paul Houser, Terence Doiron, Peggy O'Neill
NASA Goddard Space Flight Center
Greenbelt, MD 20771, USA

Ralph Girard
Canadian Space Agency
Montreal, Canada

Dara Entekhabi
Department of Civil and Environmental Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

Abstract—The HYDROS mission is under development by NASA as part of its Earth System Science Pathfinder (ESSP) program. HYDROS is designed to provide global maps of the Earth's soil moisture and freeze/thaw state every 2-3 days, for weather and climate prediction, water and carbon cycle studies, natural hazards monitoring, and national security applications. HYDROS uses a unique active and passive L-band microwave system that optimizes measurement accuracy, spatial resolution, and coverage. It provides measurements in nearly all weather conditions, regardless of solar illumination. The designs of the radar and radiometer electronics, antenna feedhorn and reflector, and science data system, are driven by specific mission and science objectives. These objectives impose requirements on the frequencies, polarizations, sampling, spatial resolution, and accuracy of the system. In this paper we describe the HYDROS mission requirements, baseline design, and measurement capabilities.

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1. INTRODUCTION

The Hydrosphere State (HYDROS) mission is one of three Earth System Science Pathfinder (ESSP) missions selected in July 2002 for further development by NASA. HYDROS is a Principal Investigator-led mission, managed by the Jet Propulsion Laboratory with the Goddard Space Flight Center, the Canadian Space Agency, the Department of Defense, universities, and industry as collaborating partners. HYDROS will advance global change research by measuring critical parameters of the Earth's water cycle state, will enhance capabilities to predict costly natural hazards, and will provide global all-weather surface hydrologic mapping in support of national defense.

Concept Overview

Knowledge of the land hydrosphere state is vital to understanding the cycling of water, energy, and carbon in the Earth system. Fluxes of these quantities over land are strongly influenced by the soil moisture and surface freeze/thaw state, through their controls on evaporation, transpiration, and carbon exchange over most of the global land surface. HYDROS is a pathfinder mission whose objective is to provide global measurements of the soil moisture and surface freeze/thaw state, focusing on regions where these factors are primary environmental controls (this excludes tropical forests where the fluxes are radiation-limited). Currently, there are neither space-borne nor in-situ networks of measurements that can provide a characterization of the global hydrosphere state. Observations by HYDROS will be continuous over a baseline mission duration of two years and will yield large science and applications gains with breakthroughs in understanding of processes linking the water, energy, and carbon cycles.

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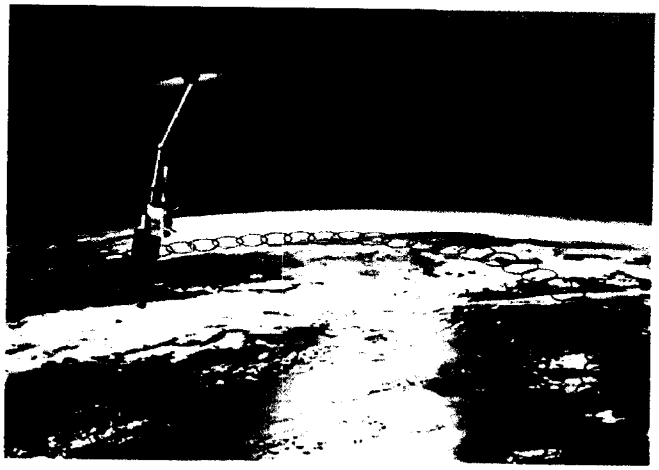

Figure 1, Schematic illustration of the HYDROS concept.

The HYDROS measurement concept is shown in Figure 1. Radar and radiometer sensors are used, with a large rotating antenna system, to measure L-band (1.2-1.4 GHz) microwave emission and backscatter from the surface across a wide swath. These measurements are converted to soil moisture, freeze/thaw state, and associated variables. The measurements are registered to an Earth-fixed grid, providing updated global maps of these variables every 2-3 days. The antenna is a 6-m diameter deployable mesh reflector that provides footprint sizes of 40 km for the radiometer and 1-3 km for the radar. The enhanced radar resolution is accomplished by unfocused synthetic aperture radar (SAR) processing. The unique feature of HYDROS is its ability to obtain simultaneous active and passive (radar and radiometer) measurements of the surface, with resulting improvements in spatial resolution and accuracy of the derived products. The key products are soil moisture at 10 km resolution, and freeze/thaw state at 3 km resolution, derived from radar and radiometer data using model data assimilation and optimal estimation algorithm techniques.

Science and Applications

HYDROS will provide new data for improved weather and climate predictions. Initialization of the prediction models with hydrosphere state measurements has been shown to significantly improve forecast accuracy and reliability [1]-[3]. HYDROS observations will also benefit climate-sensitive socioeconomic activities (water management, agriculture, and fire, flood, and drought hazards monitoring) by extending the capability to predict regional water availability and seasonal climate. In boreal ecosystems, early spring thaws lead to significant increases in net carbon uptake [4], [5]. The timing of the freeze/thaw transition, as measured by HYDROS, is key to quantifying boreal landscape carbon exchange with the atmosphere. In polar regions, HYDROS will provide frequent, high-resolution, all-weather information on sea-ice extent and dynamics, enhancing the existing operational capabilities. HYDROS will also provide information on ocean salinity, though with less accuracy than the Aquarius mission [6].

HYDROS L-band measurements are responsive to the status of water in the top ~5-cm soil layer. However, information on soil moisture and freeze/thaw conditions at deeper layers through the root zone is desirable to fully determine the impact of these parameters on surface-atmosphere fluxes of water, energy, and carbon. Thus, HYDROS measurements will be merged with data from *in situ* sensor networks and other satellites in a modeling and data-assimilation framework, to produce value-added products including moisture through the root zone.

The relationship between soil moisture and surface evaporation at a specific site is shown in Figure 2(a) [7]. The fractional surface evaporation (with respect to its upper limit, potential evaporation) depends strongly on surface soil moisture, shown here as measured by a ground-based L-band radiometer. The correct model representations of this relationship and the corresponding relationship for runoff ratio (ratio of runoff to precipitation), are critical for climate and global change studies. HYDROS measurements provide the required missing soil moisture element for performing such stringent tests of land surface models.

The ecosystem transition from carbon source to sink, coincident with thaw, is shown for a boreal site in Figure 2(b). Ecosystem process simulations over multiple years for boreal forest stands show 6- to 7-week ranges in the timing of soil thaw [8]. These variations result in substantial effects on ecosystem carbon productivity; they can determine the magnitude of annual carbon exchange and whether the ecosystem is altogether a net source or sink of atmospheric carbon.

2. System Description and Requirements

The HYDROS system design is an outgrowth of studies conducted over the past several years to evaluate the use of lightweight deployable mesh antennas for remote sensing applications requiring low frequency and/or high spatial resolution [9], [10]. Soil moisture, freeze-thaw, and ocean salinity sensing all require low frequency (L-band) large-aperture antennas to achieve desired measurement sensitivities and spatial resolutions [11]-[13].

The top-level design elements of the HYDROS system are shown in Table 1. The baseline HYDROS design characteristics are described below. However, some of these characteristics (for example in the electronics and antenna subsystems) are being refined as a result of trade-off studies performed during the mission formulation phase.

The HYDROS spacecraft is designed for a 670-km circular, Sun-synchronous orbit, with equator crossings at 6 am and 6 pm local solar time. The instrument combines radar and radiometer subsystems that share a single feedhorn and parabolic mesh reflector. The radar operates with VV, HH, and HV transmit-receive polarizations, and uses separate transmit frequencies for the H (1.26 GHz) and V (1.29 GHz) polarizations. The radiometer operates with V, H and U (third Stokes parameter) polarizations at 1.41 GHz. The U-channel measurement is to assist in the correction of Faraday rotation effects.

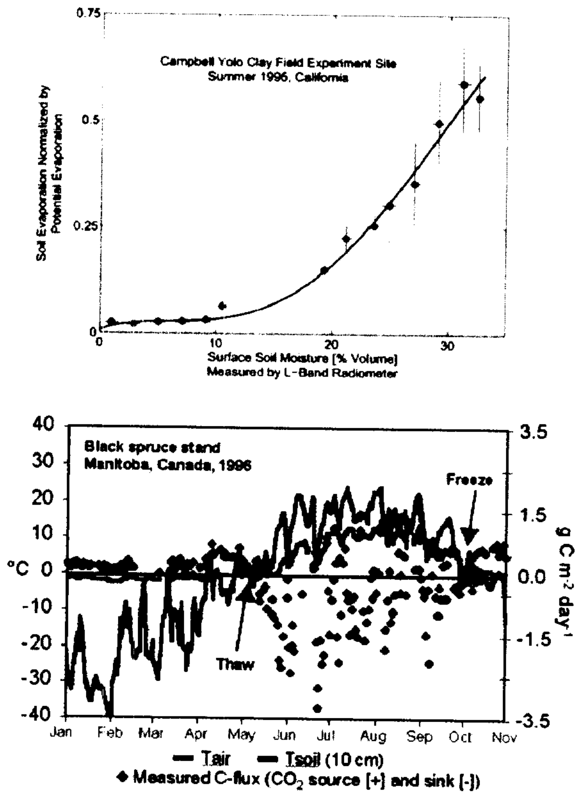

Figure 2. (a) Dependence of evaporative fraction on surface soil moisture (upper panel). (b) Impact of freeze/thaw transition on land-atmosphere carbon flux.

The reflector is offset from nadir and rotates about the nadir axis at 14.6 rpm, providing a conically scanning antenna beam with a surface incidence angle of approximately 40°. The feedhorn is fixed and does not rotate with the reflector. To maintain a polarization that is fixed with regard to the surface, the feedhorn assembly incorporates a pin polarizer that rotates synchronously with the reflector. The reflector diameter is 6 m, providing a radiometer footprint of approximately 40 km (root-ellipsoidal area) defined by the one-way 3-dB beamwidth. The two-way 3-dB beamwidth defines the real-aperture radar footprint of approximately 30 km. The real-aperture ('lo-res') swath width of 1000 km provides global coverage within 3 days at the equator and 2 days at boreal latitudes (> 50° N). Figure 3 illustrates the instrument and conical scanning configuration.

To obtain the desired 3-km spatial resolution, the radar employs range and Doppler discrimination. While similar to standard synthetic aperture radar (SAR), the aperture length of HYDROS is quite short (32 ms), simplifying the processing. Due to squint angle effects, the 3-km resolution cannot be achieved within a 300-km swath region centered on the nadir track. The 3-km ('hi-res') portion of the swath is thus defined as the two outer 350-km-wide segments shown in Figure 3.

Table 1. HYDROS design elements

- Conically scanning, deployable, mesh reflector
- Simultaneous active and passive measurements at constant 40° incidence angle (shared antenna)

Radar:
 1.26-1.29 GHz (VV, HH, HV)
 1-3 km high-resolution
 3-30 km low-resolution
Radiometer
 1.41 GHz (V, H, U)
 40 km resolution
Swath: 1000 km for frequent global mapping
Revisit:
 2-3 days globally
 1-2 days above 45°N
Orbit:
 670 km altitude
 Sun-synchronous, 6 am / 6 pm

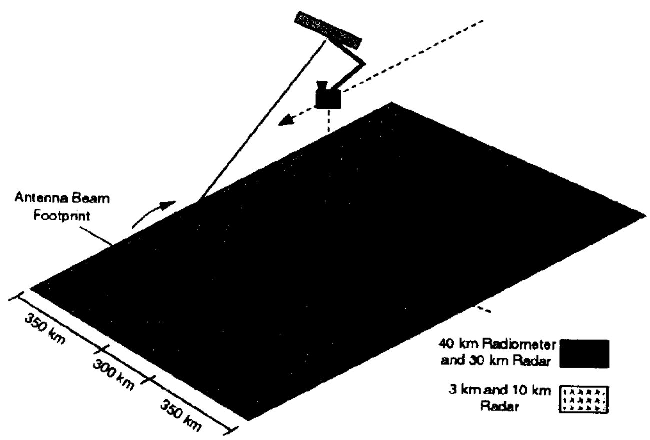

Figure 3. Conical scan configuration, showing 'hi-res' and 'lo-res' swath limits.

The instrument block diagram is shown in Figure 4. The radar and radiometer systems, mounted on the upper deck of the spacecraft, share the dual polarized feed assembly and the deployable mesh reflector supported by a deployable boom. In the baseline design, the reflector is the only rotating component and is rotated by a reflector spin motor, providing the required conical scanning for the two systems. The radiometer commanding and data handling (C&DH) is provided directly by the spacecraft; the radar C&DH electronics is housed within the spacecraft VME chassis.

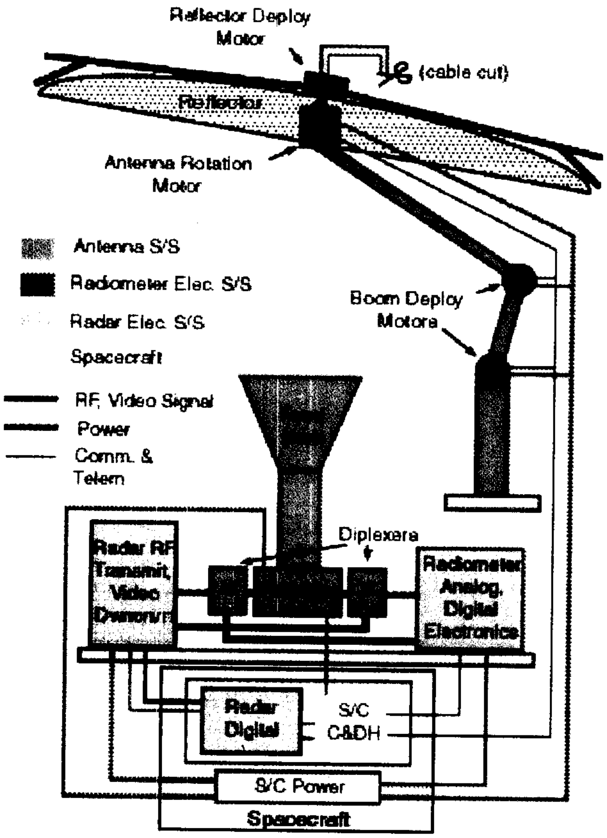

Figure 4. HYDROS instrument system block diagram

Operating Modes

The radiometer operates continuously, generating a relatively low (12.8-kbps) data rate. The radar operates in two modes: a high-resolution mode for generating 3-km and 10-km geophysical products, and a low-resolution or real-aperture mode. In the high-resolution mode, each fully sampled radar return is digitized, compressed using block floating point quantization (BFPQ), recorded by the onboard recorders, and downlinked for range and azimuth compression processing on the ground. The peak data rate out of the instrument is 31.7 Mbps. In low-resolution mode, each radar return is incoherently averaged into ten range bins and no azimuth compression is performed. This averaging is done on the spacecraft, resulting in 3-km × 30-km cells and a 60.0-kbps peak data rate.

To reduce the power consumption, data rate, and data volume, both radar modes operate only over the forward arc of the conical scan. To reduce the data rate and volume further, the high-resolution mode operates only over land and over the descending (am) portion of the spacecraft orbit. These factors lead to 15.9-Mbps and 41.0-kbps average data rates, respectively. The average radar data rate and volume may be reduced further by less frequent operation of the HV channel. This channel is used primarily for radar vegetation determination. Because the vegetation is not be expected to vary on the same temporal scale as the soil moisture, the HV channel is planned be operated only one out of every five days.

System Requirements

The functional requirements are derived through a traceability analysis, summarized in Table 2. The system parameters are listed in Table 3. These parameters are currently being refined in design trade studies. The radar uses separate frequencies for the horizontal (H) and vertical (V) polarizations. This is necessary to satisfy range and azimuth ambiguity constraints imposed by the high-resolution radar mode. These ambiguities are limited by design to – 20 dB. The ambiguity constraints determine a pulse repetition frequency (PRF) of approximately 3500 Hz. This PRF applies to both frequencies (or polarizations), which are transmitted simultaneously. The PRF varies slightly over each orbit due to the oblateness of the Earth.

The performance requirements in Table 3 include the radiometer integration time and bandwidth, and the radar pulse width, bandwidth, peak power, and minimum number of looks for a given resolution. Each of these are related to the respective performance requirements in Table 2. For example, the radiometer relative error requirement is derived directly from the soil moisture measurement requirement. Relative error includes measurement precision, due to thermal noise, and calibration stability. Measurement precision for the radiometer is inversely proportional to the square root of the bandwidth and integration time (the time-bandwidth product). The reflector rotation rate of 14.6 rpm is determined by the requirement for footprint overlap at the surface. With this rotation rate the available integration time for each measurement is 42 ms. This is effectively doubled when both fore- and aft-looking measurements are combined. With a measurement bandwidth of 25 MHz and system noise temperature of 590 K, the resulting precision is 0.4 K. The calibration stability is estimated at 0.5 K. The root sum square of the calibration stability and the precision yields a total estimated relative error of 0.64 K, satisfying the 1-K requirement of the soil moisture science objective.

Two requirements placed on the radar relative error. The soil moisture measurement requirement places a 0.5-dB relative error requirement for both vertical and horizontal co-polarized backscattering coefficient (σ_o) measurements at 10-km resolution. The freeze/thaw state measurement places a 1.0-dB requirement on the relative error of each vertical and horizontal co-polarized σ_o measurement at 3-km resolution. The radar relative error depends on the signal-to-noise ratio (SNR) and the number of independent samples, or "looks", averaged in each measurement, as well as the relative calibration error. The number of looks is obtained by averaging in both range and azimuth. The 1-MHz bandwidth yields a ground range resolution of approximately 250 m and results in a minimum of 12 looks in range for 3-km cells and 40 looks for 10-km cells. The number of azimuth looks is dependent on the one-look azimuth resolution.

Table 2. HYDROS functional requirements traceability

Scientific Measurement Requirements	Instrument Functional Requirements	Spacecraft and Mission Requirements
Soil Moisture: ~±4% volumetric accuracy in top 2-5 cm for vegetation water content < 5 kg m^{-2} Hydrometeorology at ~10km Hydroclimatology at ~40km	*L-Band Radiometer:* Polarization: V, H, U; Resolution: 40 km; Relative accuracy: 1 K *L-Band Radar:* Polarization: VV, HH, HV; Resolution: 10 km; Relative accuracy: 0.5 dB for VV and HH Constant Incidence angle between 35°-50°.	Total system boresight pointing: 0.34° accuracy 0.30° stability 0.1° knowledge On-board storage of at least 3 orbits of science data S-Band downlink for radiometer and global radar (2.5 Mbps) X-Band downlink for Hi-Res radar (80 Mbps)
Freeze/Thaw State: Capture freeze/thaw transitions in integrated vegetation-soil continuum with two-day precision, at spatial scale of landscape variability (~3 km).	*L-Band Radar:* Polarization: HH; Resolution: 3 km Relative accuracy: 0.7 dB (1 dB per channel if two channels are used.) Constant incidence angle between 35°-50°.	
Sample diurnal cycle at consistent time of day (6 am / 6 pm) Global: ~3 day revisit Boreal: ~2 day revisit	Swath Width: ~ 1000 km	*Orbit:* 670 km circular polar, sun-synchronous, ~6am/6pm equator crossing
Observation over a minimum of two annual cycles	Minimum two-year mission life	Two-year baseline mission.

Table 3. HYDROS performance requirements

Radiometer beamwidth (1-way)	2.6°		
Radar beamwidth (2-way)	1.9°		
Off-nadir look angle	35.0°		
Incidence angle	39.3°		
Peak gain	36 dBi		
Rotation rate	14.6 rpm		
Radiometer:			
Center frequency	1.41 GHz		
Footprint (root ellipsoidal area)	38 km		
Channels (each beam)	H, V, U		
Bandwidth, Integration time	25 MHz, 84 msec		
Precision (noise equivalent ΔT combining fore/aft meas)	0.4 K		
Calibration stability	0.5 K		
Total relative error	0.64 K		
Radiometer:			
Transmit Frequencies	1.26 GHz (H), 1.29 GHz (V)		
Channels (each beam)	HH, VV, HV		
PRF, Pulse Length	3.5 kHz, 15 msec		
Maximum aperture length	32 ms		
Transmit bandwidth	1 MHz		
Peak transmit power	500 W		
Noise equivalent σ^o	-39 dB		
Product resolution (km)	3	10	30
Total # looks (worst case, outer swath)	24	267	2400
Relative calibration error (dB)	0.4	0.35	0.3
Total relative error (dB) (1σ ea. channel, HH and VV)	1.0	0.45	0.3

The radar uses Doppler discrimination to increase azimuth resolution. Figure 5 illustrates the measurement geometry, with a particular focus on the iso-Doppler contours. The direction of the platform is labeled as v_g; the scan angle is labeled as θ_{az}. The azimuth resolution is dependent on the total Doppler bandwidth resolved in each footprint. The Doppler diversity is maximum at a scan angle perpendicular to the platform velocity, leading to a single-look azimuth resolution of approximately 450 m. The single-look resolution decreases as the scan angle approaches the platform velocity vector, reaching 1500 m at the inner swath edge (150-km cross-track).

Because the number of azimuth looks in a given cell varies linearly as a function of the cross-track distance, the measurement requirement is placed over the outer 350 km of the swath, as illustrated in Figure 3. In the outer swath, the minimum number of looks in a 3-km cell is 24, while the minimum number in a 10-km cell is 267 (Table 3). With a signal-to-noise ratio of 9 dB and the given minimum number of looks, the radar measurement precision can be calculated. When the precision is root-sum squared with the relative calibration error, the resulting 3-km total relative error is 1 dB, while the 10-km relative error is 0.45 dB. These values are worst cases for the outer swath, since the number of looks increases substantially as the cross-track distance increases.

3. INSTRUMENT ARCHITECTURE

The HYDROS instrument architecture was selected to meet the performance requirements while presenting the lowest possible risk and cost. As shown in Figure 4, the instrument is divided into three major subsystems: (1) The antenna subsystem, which includes the deployable mesh reflector, supporting deployable boom, reflector spin motor, antenna feed horn, feed polarizer, and diplexers; (2) the radiometer electronics subsystem, and (3) the radar electronics subsystem.

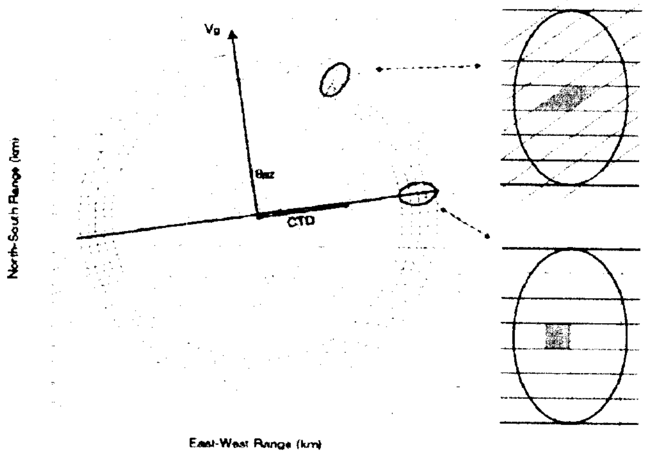

Figure 5. HYDROS radar measurement geometry

The reflector is deployed and supported by the antenna boom. In the baseline design only the reflector rotates; the boom and feed assemblies are fixed on the spacecraft. This approach yields a minimum rotational inertia, is straightforward to spin-balance during pre-launch testing, and involves no rotating electrical interface (such as RF rotary joints or slip rings). An alternative design is under study, in which the boom supports the reflector at the reflector rim, and the boom and reflector (and possibly the feed also) rotate together. This avoids blockage of the antenna aperture by the boom, and, if the feed rotates with the reflector, avoids the need for a pin-polarizer as discussed below. Two vendors of large-aperture mesh reflectors with flight heritage designs have been identified for the two alternate systems under study (Figure 6).

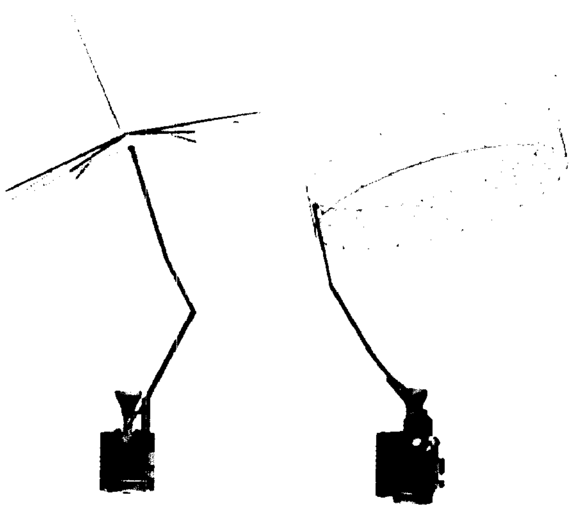

Figure 6. Antenna and boom concepts — radial rib on left, perimeter truss on right.

A single feed horn is used for both the radar and radiometer measurements and for both V and H polarizations. In the baseline configuration, to maintain a polarization that is fixed with regard to the surface, a pin polarizer is used that rotates mechanically in the throat of the feed horn, synchronously with the reflector. The rotation of the polarizer is synchronized to the reflector rotation by signals from the spacecraft CPU, which, in turn, receives position information from the reflector spin motor. The antenna feed assembly also contains diplexers for each polarization channel to separate the 1.26- and 1.29-GHz radar from the 1.41-GHz radiometer signals for routing to their respective electronics.

The radiometer electronics subsystem is mounted on the zenith deck of the spacecraft, as close to the feed assembly as possible. A digital interface with the spacecraft C&DH is provided to transfer the radiometer science measurements and telemetry to the spacecraft recorder for transmission to the ground. The radiometer receives a timing signal to protect the receiver during radar transmit events. The radar RF electronics assembly, which creates the transmit pulses and amplifies and down-converts the return echoes, is also mounted on the zenith deck of the spacecraft. The radar digital electronics assembly, which governs the radar timing and performs digital processing on the return echoes, is located within the spacecraft avionics VME card cage, yielding a lower cost integrated design. The software necessary to command the radar timing and high-rate data collection is implemented on the spacecraft CPU. Radar data are transferred to spacecraft recorder via the high-speed interface within the VME cage.

All critical deployment pyros and actuators are designed for redundancy. To minimize mass and cost, a single-string approach will be used for the majority of the instrument components. The term "single-string," however, does not by itself adequately describe the inherent reliability associated with the instrument design. Both the radar and radiometer electronics employ two polarization channels. Consequently, if any single channel fails, the science mission degrades in a graceful fashion. The instrument design is consistent with a two-year on-orbit life.

To achieve the desired 36-dBi minimum antenna gain at 1.26 GHz, a reflector with a 6-m-diameter projected aperture is required. The reflector focal length is chosen to be as large as possible to minimize polarization degradation, and is limited by the maximum allowable boom length and by the stowed volume allocated inside the vehicle fairing. A 5.36-m focal length was selected for the preliminary design of the antenna, with a 0.25-m offset of the circular aperture with respect to the vertex of the parent paraboloid. To meet the pointing and gain stability requirements, the reflector surface must maintain its shape to within 2.5 mm under all dynamic and environmental conditions.

The reflector/boom assembly requirements/components are: (1) 6-m projected aperture, solid-rib or perimeter truss, foldable, wire-mesh reflector with deployment motor actuator; (2) segmented, deployable boom; (3) boom deployment actuators; (4) launch latch/release mechanisms; (5) reflector spin mechanism and motor-drive electronics; (6) spacecraft attachment struts; and (7) pyro cable cutter. The design of the reflector/boom is driven by the on-orbit size and position of the deployed reflector, juxtaposed with the need to stow the subsystem within the Taurus (or equivalent launch vehicle) shroud. In its deployed configuration, the reflector rotates around the extended centerline of the feed horn at the desired 14.6 rpm. Balance weights are placed on the reflector to keep its cross products of inertia and static imbalance at a minimum; this eliminates unwanted wobble of the spinning system and its adverse effect on the spacecraft attitude control system. For launch, the reflector is folded, stowed, and latched against the spacecraft bus (Figure 7).

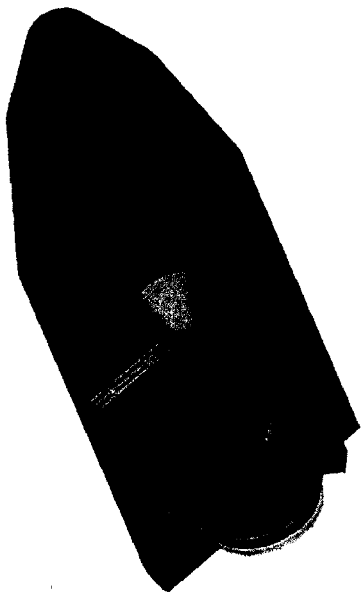

Figure 7. Stowed reflector configuration.

4. Summary

This paper has reviewed the science rationale and applications of the HYDROS mission, and has provided a description of the instrument requirements and design. The HYDROS mission is currently in the formulation phase, with an estimated launch date in 2010. During the formulation phase refinement of the HYDROS mission design will continue, leading to a design that fully optimizes the trade-offs between science yield, risk, and cost. The HYDROS mission will be a centerpiece of the NASA Earth science water and energy cycle program, as well as augmenting the operational weather and national security capabilities.

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