The Hydrosphere State (HYDROS) Mission

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Abstract: The Hydrosphere State (HYDROS) Mission has been selected for the National Aeronautics and Space Administration (NASA) Earth System Science Pathfinder (ESSP) program. The objectives of HYDROS are to provide frequent, global measurements of surface soil moisture and surface freeze/thaw state. In order to adequately measure these geophysical parameters, a system capable of simultaneously measuring L-Band radiometer brightness temperatures at 40 km resolution and L-Band radar backscatter at 3 km resolution over a very wide swath is required. In addition, these science requirements must be satisfied under the stringent cost-cap imposed on all ESSP missions. As a solution to this challenging set of requirements, a relatively large, six meter, conically-scanning reflector antenna architecture was selected for the mission design. The HYDROS instrument will fly on a General Dynamics SA-200HP spacecraft bus. Although large deployable mesh antennas have been used in communication applications, this will mark the first time such technology is applied in a rotating configuration for high-resolution remote sensing.

I. Introduction

THE Hydrosphere State (HYDROS) Mission has been directed to proceed with mission formulation as part of the most recent NASA Earth System Science Pathfinder selection (ESSP-3). The primary objectives of HYDROS are to provide frequent, global measurements of surface soil moisture and surface freeze/thaw state. Measurements of soil moisture and freeze/thaw state are critical components in approaching high-priority questions in Earth system science today. These include key questions about the water and energy cycle as well as the carbon cycle. In addition, measurements of soil moisture and freeze/thaw state provide increased capability to predict costly natural hazards such as extreme weather, floods, and droughts. HYDROS measurements will also have a national security return, enhancing overall weather and terrain trafficability prediction for military decision making.

The key driving science requirements for HYDROS mission are: 1) Measure hydroclimatology and hydrometeorology soil moisture at spatial resolutions of 40 km and 10 km respectively, 2) Measure freeze/thaw state at a spatial resolution of 3 km, 3) Obtain measurements at a temporal sampling rate of 2-3 days globally under all weather conditions, 4) Obtain a sustained series of global measurements for a minimum of two years.

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II. Overall System Architecture and Approach

Soil moisture and freeze/thaw state will be obtained by using a combination of passive and active microwave measurements of the Earth s surface. Both radiometer and radar measurements have been shown to be sensitive to soil moisture (Ref. 1). In order to minimize the impact of vegetation on the soil parameter retrievals, both active and passive HYDROS measurements will be obtained at L-Band frequency. Under vegetated conditions, radiometric retrieval algorithms currently provide more accurate soil moisture estimates. The radar measurements, on the other hand, are capable of a higher spatial resolution and provide sub-pixel roughness and vegetation information. Hence, the combination of simultaneous radar and radiometer data can enhance the resolution capability and accuracy of the soil moisture estimates. The inclusion of radar is also critical for the determination of freeze/thaw state at the required 3 km resolution.

As with most microwave instruments, the antenna is the dominant instrument subsystem that both determines the ultimate measurement performance and governs spacecraft accommodation. In order to meet the 3-day revisit requirement at the equator, a wide measurement swath is necessary. The radiometer and radar resolution requirements at L-Band dictate that a relatively large antenna aperture must be employed. As determined by previous trade-off studies (see Ref. 2), the most economical approach for accomplishing the required simultaneous radiometer and radar requirements is to utilize a shared antenna/feed approach. A reflector antenna was chosen to ensure that system calibration requirements, primarily for the radiometer, are met. As shown in Figs. 1 and 2, rotating the reflector in a conical fashion about the nadir axis provides a wide swath of measurements at a constant incidence angle. A variety of other instrument architectures were considered (phased array, separate antennas for radiometer and radiometer, etc.), but the scanning, shared reflector approach was found to be optimum in terms of maximizing performance while minimizing implementation cost and risk.

The spatial resolution of the radiometer measurements are determined by the dimensions of the antenna beam footprint projected on the Earth s surface. To obtain the required high-resolution radar data, range and Doppler discrimination will be employed. This is equivalent to the application of synthetic aperture radar (SAR) techniques to the conically scanning radar case (see Ref. 3). Due to squint angle effects, the high-resolution products will not be obtained within a narrow swath band centered on the spacecraft nadir track (see Fig. 2).

The requirement for global coverage and constant diurnal sampling leads to the selection of a near-polar, sun-synchronous orbit. A series of trade studies was performed in order to select the optimum combination of orbit altitude and antenna parameters to simultaneously meet the 2-3 day temporal revisit requirement and the instrument spatial resolution requirements. Higher orbits have the advantage of larger swaths — and hence better revisit statistics — but require larger antennas to meet the spatial resolution requirements due to the increased slant range to the surface. The nominal HYDROS altitude was selected to be 670 km. At this altitude, a six meter diameter antenna scanning a total swath of 1000 km is required to meet the measurement requirements (see Table 1).

The HYDROS flight system consists of the HYDROS instrument and spacecraft. Taken together, these two elements constitute the HYDROS observatory. The baseline designs for these two major elements, as well as their respective design rationale, are discussed in the following two sections.

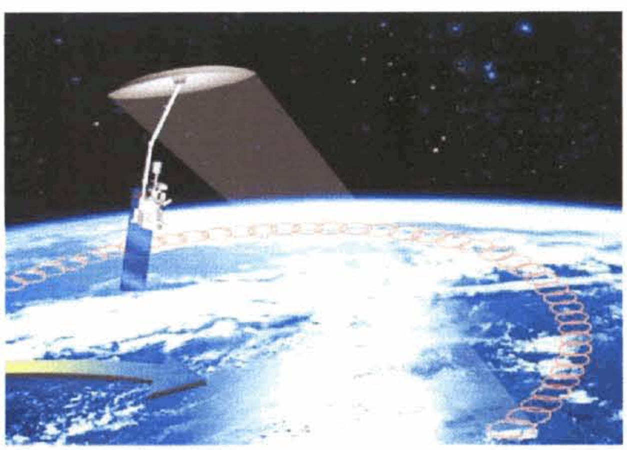

Figure 1. Artist s depiction of HYDROS observatory in orbit.

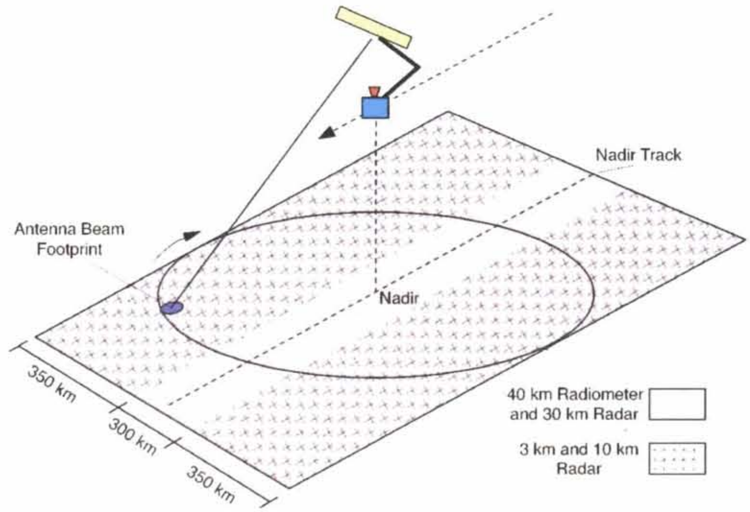

Figure 2. HYDROS measurement geometry showing radiometer swath, and high and low resolution radar swaths.

III. HYDROS Instrument

Instrument partners include the Jet Propulsion Laboratory (JPL) (overall instrument management and radar electronics), NASA Goddard Space Flight Center (GSFC) (radiometer), and the Canadian Space Agency (CSA) (antenna design and feed assembly). Large, rotating antennas have been proposed for L-Band remote sensing in the past (Ref. 2). Typically, these proposals have involved construction of a spin table upon which the antenna, supporting structure, feeds, and microwave electronics are mounted. The entire table is then rotated to form the swath. Telemetry and power between the de-spun spacecraft and spun electronics is passed through a slip ring interface. With such a design, it is often advantageous to locate the high power radar electronics on the de-spun spacecraft side. When this is the case, an RF rotary joint must also be provided across the spun/de-spun interface. Such a spin table approach therefore involves a relatively massive rotating structure and numerous interfaces between the spun and de-spun sections.

In contrast to the spin table antenna architecture, the baseline HYDROS approach involves rotating the antenna reflector only (see Fig. 3). The feed and instrument electronics are all fixed to the de-spun spacecraft. The single feed is aligned with the rotational axis of the antenna, so when the reflector is spun, the resulting beam forms a conical scan. This approach has the advantage of minimizing the total spun mass, as well as eliminating all spun/de-spun electrical interfaces. Note, however, that for a fixed feed with a fixed set of linear polarization axes, the polarization with respect to the surface will rotate with the reflector position and will not be aligned with the desired horizontal and vertical axes. Compensation for this effect is straightforward, but handled differently for the radiometer and radar (as discussed below).

Due to the relatively large size of the required reflector (6-meter projected aperture), a deployable structure is necessary. Deployable mesh reflector technology is quite mature for spaceborne communications applications, and analyses of the mesh material have indicated its acceptability for remote sensing applications (Ref. 2). The unique aspect of the HYDROS application is the necessity for rotating the antenna. At the nominal HYDROS altitude of 670 km, the reflector must be rotated at a rate of 14.6 rpm to maintain contiguity (i.e., minimum overlap) of the measurements in the along-track direction. Key requirements that must be met by the reflector assembly include: 1) All RF performance requirements (gain, beam efficiency, etc.) must be met under the spinning conditions, 2) The total momentum generated must be within the amount the spacecraft is capable of compensating, and 3) The disturbances resulting from residual imbalances must be sufficiently small as to not effect overall pointing or impart excessive loads to the spin motor bearings. Two designs for the reflector/spin assembly are being developed in parallel for eventual down-selection (see Fig. 4). Both designs are based on flight-proven mesh reflector technology. One involves application of a radial rib reflector design, and the other the application of a perimeter truss reflector design.

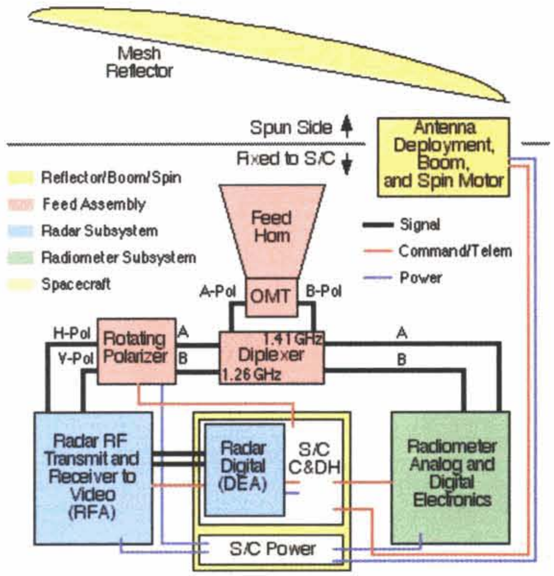

Figure 3. HYDROS instrument functional block diagram.

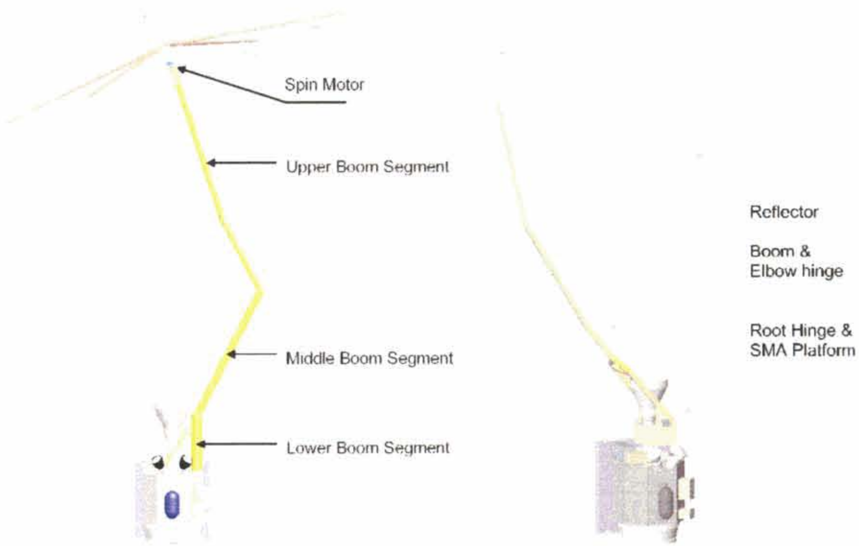

Figure 4. Two concepts for HYDROS rotating 6-meter deployable mesh reflector. On the left, a Radial rib type reflector will be rotated at central hub at upper tip of boom (image courtesy of Harris Corp.). On the right, a Perimeter truss type antenna to be grasped by boom on reflector edge and rotated by motor positioned down on zenith deck of spacecraft (image courtesy of Astro Aerospace, Northrop Grumman Space Technologies).

The baseline feed assembly design employs a single smooth-wall horn, capable of dual-polarization and dual frequency (radiometer frequency at 1.41 GHz, and the radar frequencies at 1.26 and 1.29 GHz). As shown in Fig. 3, the radar and radiometer frequencies will be separated by diplexers and routed to the appropriate electronics for detection. As mentioned previously, because the feed is fixed and the reflector is rotating, the two linear feed polarizations (denoted A and B) will rotate relative to the desired horizontal and vertical polarizations (denoted H and V) with respect to the surface. For the radiometer measurements, the strategy is to measure the first three modified Stokes parameters T_A, T_B, and U_{AB}. These measurements, together with knowledge of the antenna position, can then be used to rotate the polarization basis to achieve a constant polarization basis orientation with respect to the surface and obtain the desired measurements T_H and T_V.

In general, the problem of rotating a set of radar measurements from one polarization basis to another requires that a fully polarimetric quad-pol system be implemented. Such an implementation is being studied for HYDROS, but the current baseline system is not fully polarimetric, and therefore the radar measurements cannot be rotated to the desired polarization basis during ground processing in an analogous manner to the radiometer measurements. As a solution to this problem, a polarizer unit — implemented with a pin-polarizer rotating synchronously with the reflector — is used to launch linear polarized signals in the desired horizontal/vertical basis with respect to the surface (see Fig. 3).

Measurement precision for a radiometer is proportional to the inverse square root of the bandwidth and the measurement integration time (the time-bandwidth product). Given a reflector rotation rate of 14.6 rpm, the available integration time for each measurement is 42 ms. That value, however, will effectively be doubled when both fore and aft looking radiometer measurements are combined. Choosing a measurement bandwidth of 25 MHz and a system noise temperature of 590 K, the resulting precision is 0.4 K. The radiometer calibration stability is estimated to be 0.5 K. Calibration stability is achieved by frequent observation of internal calibration sources and stable thermal design. The root-sum square of 0.5 K and the 0.4 K stability and precision specifications yield a total random error of 0.64 K, satisfying the 1 K requirement of the soil moisture science objective. A consideration of radio-frequency interference (RFI) is important to the design. Multiple methods of handling RFI are being considered: simple filter, limiting, and pulse detection and temporal blanking. These methods are compatible with the basic radiometer design; temporal blanking as an RFI mitigation technique is attractive because a blanking scheme is already planned for mitigating the HYDROS radar pulses in the radiometer. These techniques will be useful for mitigating ground-based radar interference such as from air-route surveillance radars.

Table 1: HYDROS instrument parameters.

Antenna Key Parameters	
Beamwidth (1-way, 3 dB)	2.6°
Look Angle, Incidence Angle°	35.0°, 39.3°
Peak Gain	36 dBi
Rotation Rate	14.6 rpm
Radiometer Key Parameters	
Center Frequency	1.41 GHz
Resolution (root footprint area)	38 km
Channels	T_A, T_B, U_{AB}
Bandwidth, Integration Time	25 MHz, 84 msec
Precision	0.4 K
Calibration Stability	0.5 K
Total Relative Error	0.64 K
Radar Key Parameters	
Transmit Frequencies	1.26 GHz (H), 1.29 GHz (V)
Channels	HH, VV, HV
PRF, Pulse Length	3.5 kHz, 15 μsec
Azimuth Dwell Time	37 ms
Transmit Bandwidth	1 MHz
Peak Transmit Power	500 W
Single-look res (broadside)	250 m x 400 m
Noise Equiv. σ^o (broadside)	-35 dB

To obtain the required 3 km and 10 km resolution for the freeze/thaw and soil moisture products, the radar will employ pulse compression in range and Doppler discrimination in azimuth to sub-divide the antenna footprint. This is equivalent to the application of synthetic aperture radar (SAR) techniques to the conically scanning radar case (see Ref. 3). Due to squint angle effects, the high-resolution products will not be obtained within the 300-km band of the swath centered on the nadir track (see Fig. 2). In order to minimize range/Doppler ambiguities with the baseline antenna and viewing geometry, separate carrier frequencies are used for each polarization (1.26 GHz for H-Pol and 1.29 GHz for V-Pol). An additional channel measures the HV cross-pol return. This frequency separation approach allows both polarization channels to be operated simultaneously with the same timing. However, since the two polarizations use separate frequencies, it is not possible to measure all the parameters of the covariance matrix, and a polarizer is used in the current baseline design.

There are 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 measurements at 10 km resolution. The freeze/thaw state measurement places a 1 dB requirement on the relative error of each vertical and horizontal co-polarized backscatter 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. Looks will be obtained by averaging in both range and azimuth. The 1-MHz bandwidth will yield a ground range resolution of approximately 250 m and will result in a minimum of 12 looks in range for 3 km cells and 40 looks for 10 km cells.

The 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 instrument 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.

IV. HYDROS Spacecraft and Mission Operations

The driving requirements which influenced the spacecraft selection for HYDROS are: 1) Ability to accommodate the HYDROS instrument — including power, data rate, momentum compensation, field-of-view, and electromagnetic interference (EMI) compatibility, 2) Mass and volume compatible with Taurus launch vehicle, and 3) Lowest possible implementation and cost risk, consistent with overall philosophy of ESSP missions. In response to these requirements, the HYDROS project selected a General Dynamics (formerly Spectrum Astro) SA-200HP spacecraft bus design very similar to that used for the Coriolis mission. Coriolis is a DoD sponsored mission, successfully launched in January 2003, which carries the WindSat polarimetric radiometer. The WindSat payload is similar to the HYDROS payload in that it is a zenith-deck mounted, microwave instrument, with a relatively large spinning section requiring an unobstructed view of the Earth below. Although the WindSat antenna is smaller than the HYDROS antenna (approximately 2 meters diameter, as opposed to 6 meters), the larger payload mass and faster spin rate combine to produce approximately the same spun momentum as generated by HYDROS (approximately 180 Nms). Because Coriolis carries a sensitive microwave radiometer, extremely low levels of EMI from the spacecraft are required. Because it also incorporates a radiometer, the HYDROS payload has a similar EMI requirement (but perhaps not quite as stringent, because of its single-frequency design).

Although the specific launch vehicle to boost HYDROS has yet to be finalized, a goal during mission concept development was to design an observatory compatible with a Taurus 2210 launch with the large (92 inch) fairing — in effect allowing the use of a Taurus 2210 or other more capable vehicle. This requirement places stringent constraints on the mass and stowed volume of the observatory. The bus design derived from Coriolis heritage again proved compatible with this requirement (see, for example, Fig. 5). The HYDROS spacecraft is a 3-axis attitude controlled spacecraft with a counter-rotating momentum wheel to zero out the momentum of the rotating antenna. A dominant issue for the HYDROS observatory is the maintenance of the required attitude control of 0.3 deg under the potential disturbances imparted by the rotating antenna. These rotation effects, and the system design requirements necessary it mitigate them, are currently in the process of being extensively studied by JPL, the spacecraft contractor, and the candidate antenna vendors during the formulation phase of the HYDROS project.

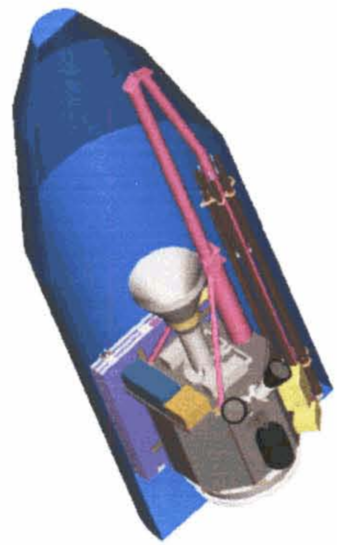

Figure 5. Example HYDROS observatory accommodation in Taurus 92 inch fairing.

HYDROS observatory flight operations will be performed primarily by the spacecraft contractor. Once the initial instrument calibration and validation (Cal/Val) phase is complete, the payload will require very little in the way of ground commands. Because HYDROS is a global observation instrument, the payload is essentially continuously generating data, with no targeting or observation scheduling commands being necessary. Although high resolution radar data — along with its associated high data rate — is only collected over land, this is easily managed with an on-orbit look-up table that stops the recording of high rate radar data when the observatory is completely over oceanic regions. The combined data rates from the radiometer and radar instruments, together with housekeeping data, generate data volume of 19 Gigabits (average) to 37 Gigabits (peak) per orbit. This data is recorded utilizing the spacecraft s 100 Gigabit capacity solid state recorder (SSR). Downlink of the science data is accomplished with an average of five ground station contacts a day at downlink frequency bands of S-Band (low rate radiometer, low rate radar, housekeeping) and X-Band (high-rate radar), with the required telemetry rates being within the standard capabilities of tracking stations in Alaska and Svalbard, Norway.

Acknowledgments

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