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# Spin-axis estimation of the Radiation Belt Storm Probes spacecraft using RF Doppler data ☆

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ABSTRACT

A methodology for using RF Doppler data for spin-axis estimation is presented. The NASA Radiation Belt Storm Probes (RBSP) mission, a dual-spacecraft mission planned for a 2012 launch, will yield valuable insights into the physical dynamics and processes of the Earth's radiation belts, particularly those that produce hazardous space weather effects and those that can affect solar system exploration. Both spacecraft have on-board Sun sensors that, in conjunction with magnetometer data, provide the required data to determine the attitude. However, the quality of the magnetometer measurements is compromised at higher altitudes because of a weaker magnetic field and also during solar storms because of variations in the Earth's magnetic field. Each spacecraft's on-board S-band radio frequency (RF) system includes a JHU/APL Frontier Radio transceiver, which provides a coherent downlink signal used for Doppler navigation. The RF system also includes two low-gain antennas offset from the spin axis with boresights parallel to the spin and anti-spin axes. Due to the spin of the spacecraft, a Doppler-induced modulation is present on the downlink carrier. Once the orbit determination is performed and the Doppler signal is analyzed, this modulation, or *spin signature*, is apparent. This spin signature can be used to accurately determine the spin rate, spin phase, and, in conjunction with Sun sensor data, the spin axis orientation. This provides a level of system redundancy with the magnetometer for attitude determination. The Sun sensor provides the angle from the spin axis to the Sun vector; the amplitude of spin signature on the Doppler data provides the instantaneous aspect angle from the spin axis to the ground station. These two measurements establish the spin axis direction. This paper describes the established theory and a method for processing the spin signature and determining the spin axis as applicable to the RBSP spacecraft. Further, RF-related errors on the Doppler carrier frequency measurement are characterized and related to the error in the spin axis orientation determination. Finally, this paper introduces the concept of attitude determination by processing the Doppler spin signature data alone over a period of time that encompasses a sufficient change to the spin axis/ground station aspect angle. This provides a further level of redundancy in the event of a failed Sun sensor. Results from processing actual data from a current mission are given.



## 1. RBSP mission description

### 1.1. Overall mission

The National Aeronautics and Space Administration (NASA) Radiation Belt Storm Probes (RBSP) mission, currently in Phase C, is scheduled for launch in May 2012. The two-year mission, designed, built, and operated by the Johns Hopkins University Applied Physics Laboratory (JHU/APL),

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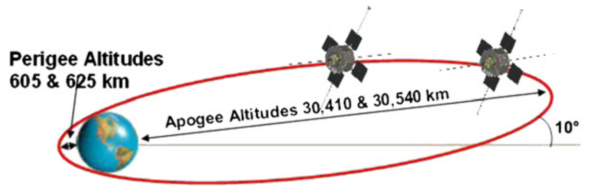


**Fig. 1.** RBSP orbit parameters. This figure shows the two RBSP spacecraft in their lapping orbits.

consists of two spin-stabilized spacecraft in a highly-eccentric Earth orbit, and will provide unprecedented insight into the dynamics of the Earth's radiation belts, in particular, the Sun's influence on Earth and near-Earth space and space weather effects [1,2].

The two RBSP spacecraft will be launched into an initial orbit (see Fig. 1) of approximately $600 \times 30{,}410$ km altitude with a $10^\circ$ inclination on a single Atlas V 401. After deployment of RBSP-A, the Atlas V will raise its own apogee to approximately 30,540 km and then deploy RBSP-B. This slight difference in apogee altitude values will cause RBSP-A to lap RBSP-B approximately once every 75 days (201 and 200 orbits, respectively).

### 1.2. Spin axis orientation

Both RBSP spacecraft are stable inertial spinners (nominally at 5 rpm), with the spin axes pointed generally in the direction of the Sun. Since the spacecraft spin axes stay inertially fixed, but the Earth moves about the Sun nearly $1^\circ$/day, it is necessary to maneuver the spin axis of each spacecraft by an average $1^\circ$/day to maintain general sun pointing. Attitude maneuvers, however, are scheduled to occur only every 21 days, during which the Right Ascension (RA) of the Sun will increase by approximately $21^\circ$. To accommodate this solar motion, the attitude maneuvers will reposition the spin axes approximately $10.5^\circ$ east (+RA) of the Sun. For the next 21 days the Sun will march eastward (in a +RA direction), passing by the spin axes on day 11, and reaching a point $10.5^\circ$ east of the spin axes on day 21. The process is then repeated throughout the duration of the mission.

Additionally, there is a seasonal North–South bias of the spin axes. When the Sun is in the Northern Hemisphere (March 21–September 21), the spin axes are offset $17^\circ$ south of the ecliptic plane, while when the Sun is in the Southern Hemisphere (September 21–March 21), the spin axes are offset $17^\circ$ north of the ecliptic plane. Fig. 2 shows the attitude control concept for both the in-plane and out-of-plane components.

### 1.3. Nominal attitude determination

A ground-based extended Kalman filter will be used to estimate the attitude of the two RBSP spacecraft. This filter uses a seven-component state vector, proposed by Markley and Sedlak [3], which includes angular momentum in both the inertial and body frames and a rotation angle. The filter incorporates data from two Sun sensors and a magnetometer on board the spacecraft. Each Sun

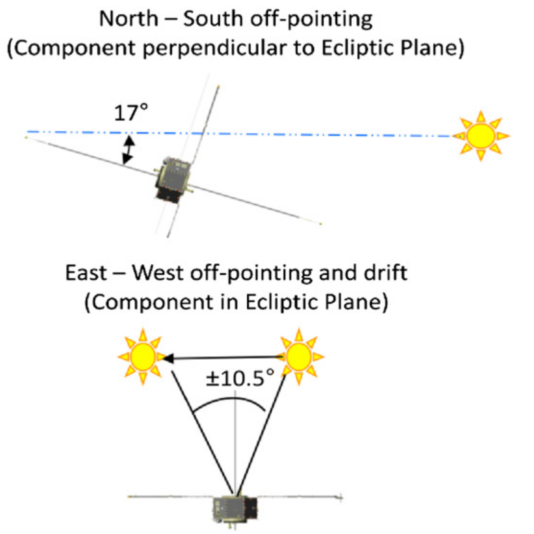


**Fig. 2.** Expected sun angles for spin axis pointing.

sensor provides one vector measurement to the sun once per spin period, which is 12 s nominally. The magnetometer measures the magnetic field in the body frame, which is then compared to the model of the magnetic field in the inertial frame. Sixty-four magnetometer measurements per second will be provided to the attitude filter.

## 2. Communications system description

### 2.1. RBSP ground stations

The mission communications system has been designed to operate with the JHU/APL 18-m ground station (APL-18) in Laurel, Maryland, USA, as the primary ground station [4]. Periodic additional contacts will be made over two United Space Network (USN) 13-m ground stations in South Point, Hawaii, USA, and Dongara, Australia, as shown in Fig. 3. These ground stations provide additional coverage for launch and early operations, emergencies, and science downlink bandwidth when needed. The spacecraft will also be compatible with the Tracking and Data Relay Satellite System (TDRSS).

### 2.2. RBSP spacecraft RF telecommunications system

The RBSP spacecraft S-band radio frequency (RF) telecommunications system has three primary functions: (1) provide a downlink for science and spacecraft housekeeping data return; (2) provide an uplink for spacecraft commanding; and (3) provide highly accurate coherent Doppler data for spacecraft navigation [5]. A block diagram of the single-string spacecraft RF system is shown in Fig. 4. The system consists of components largely designed and built by JHU/APL. The RF system features the JHU/APL Frontier Radio, which generates a coherent S-band downlink based on the received uplink frequency [6,7], and interfaces with the spacecraft Command and Data Handling (C&DH) subsystem. A JHU/APL-built 8-watt