Preliminary assessment of SpinSat SLR observations

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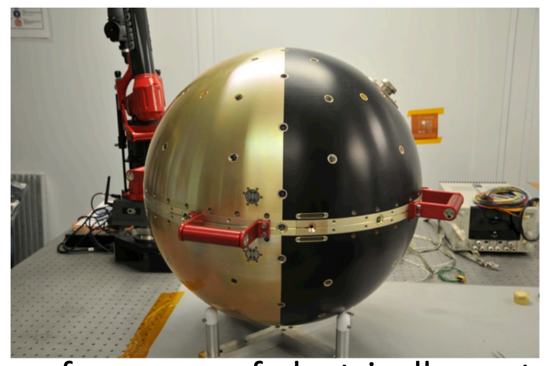
Abstract



The Special Purpose Inexpensive Satellite (SpinSat) from the Naval Research Laboratory and Digital Solid State Propulsion, LLC was deployed from the International Space Station on November 28, 2014, and is expected to reach full orbit decay in May 2016. SpinSat's primary mission is to demonstrate and characterize the on-orbit performance of electrically controlled solid propellant thruster technology in space. The thrusters are aligned so as to induce small on-orbit translational displacements and angular momentum changes of the spacecraft. An array of laser retro-reflecting corner cubes permits ground-based laser ranging for precision orbit determination, along with monitoring of total atmospheric neutral density and spacecraft spin rate and attitude. Our preliminary analysis of the high-precision International Laser Ranging Service (ILRS) ground tracking observations indicates an average coefficient of atmospheric drag, C_d, of 1.90 +/- 0.59. Initial analysis of SLR high-rate data indicates a slowly spinning spacecraft (P=567s) oriented at RA=333.0°, Dec=4.1°. For this paper, we have reanalyzed the ILRS observations using GEODYN II. We present an assessment of the reconstructed orbits and estimates of atmospheric drag, along with an estimate of initial spin rate and attitude. Future work will include modifying the analysis to include U.S. Space Surveillance Network (SSN) observations, which should improve the orbits and enhance C_d estimates. Future efforts will also use lessons learned here about the method for determining spin rate and attitude, and focus on refining the approach.

Mission Concept — A

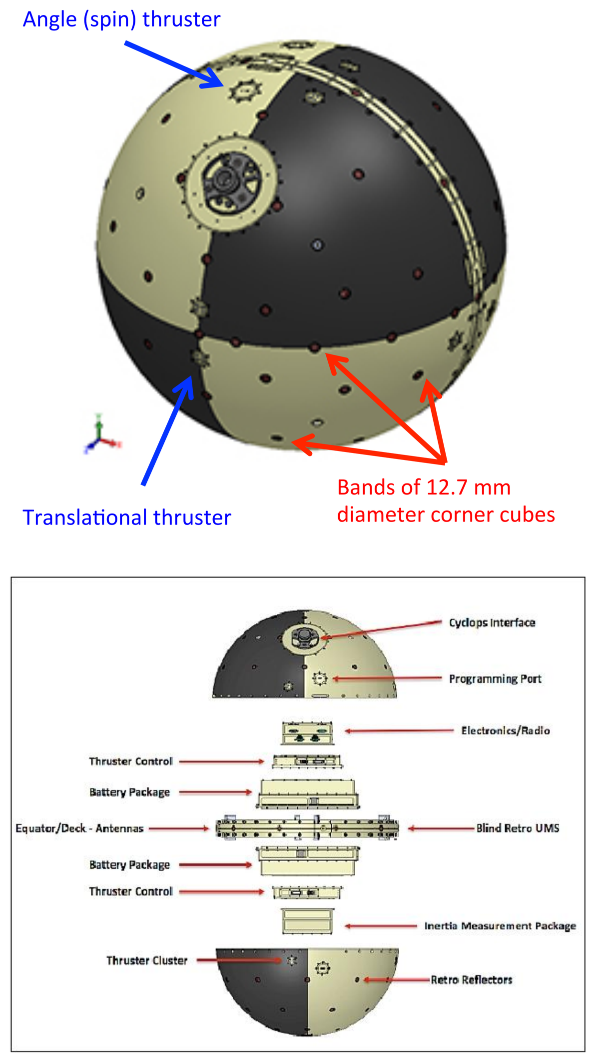


Figure A.1. Illustrations of the SpinSat spacecraft.

SpinSat was designed to perform a spaceflight demonstration of advanced rocket/projectile thruster technology that employs a special new class of electrically-controlled solid propellants (ESPs). Thrust events occur as 5 x 0.2 ms pulses. Each pulse exerts a force of 0.075 N.

ESP thrusters were arranged to induce small angular momentum changes about the spin axis, and translational motions parallel to the spin axis.

68 retro-reflecting corner cubes were mounted flush with the spacecraft outer skin to enable satellite laser ranging (SLR). High-rate SLR enables independent spin rate and attitude determination.

The spherical spacecraft has a well-determined ballistic coefficient, so it acts as primary sensor for monitoring total neutral atmospheric density. Ground-based ranging observations will provide a high-resolution atmospheric drag data set.

ILRS Tracking — B

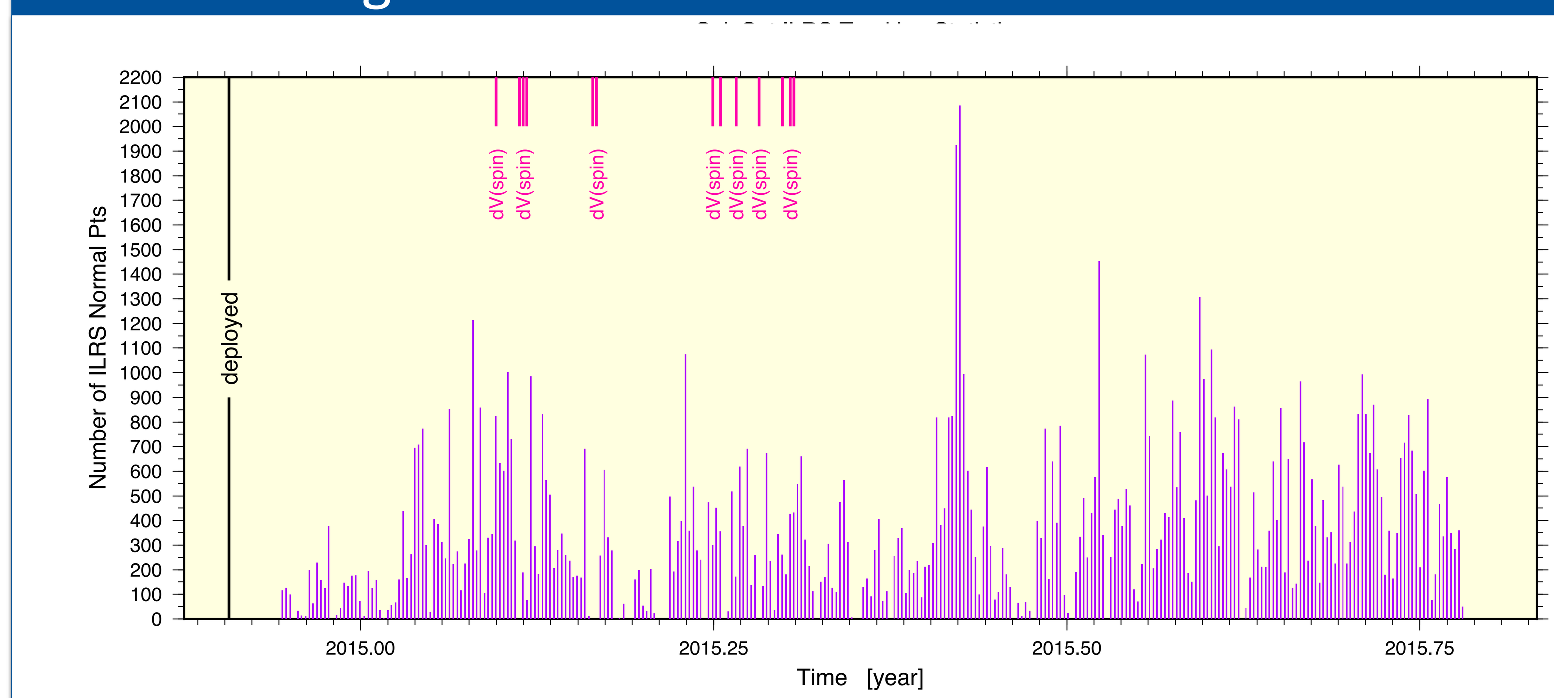


Figure B.1. Vertical violet bars indicate daily ILRS tracking levels for SpinSat. Spinsat was delivered to the International Space Station on 23 September 2014 aboard the Space-X CRS-4 Dragon resupply mission. It was deployed on 28 November 2014, and the Yarragadee ILRS Station was the first station to being tracking it on 11 December 2014 using NRL-provided orbit predictions. NRL executed several periods of thrust maneuvers (dVs) in early 2015.

NRL-provided orbit predictions generated using OCEAN [*Middour et al.*, 2000], assimilate observations from the ILRS and the U.S. Space Situational Network (SSN).

As of 12 October 2015, **~108k SLR normal points** have been collected over 306 days by 21 ILRS tracking stations. High-rate observations for spin rate and attitude determination have been provided by the Graz, Herstmonceux, and Changchun stations.

SpinSat Orbits — C

The SLR normal point and high-rate kHz data were reprocessed using the NASA/GSFC GEODYN II orbit determination software with the following setup:

- IERS 2010 Conventions generally implemented/adopted
  - geopotential field: GOCO02s static field; SLR+DORIS+GRACE-based seasonal and annual time varying gravity (TVG) models [courtesy F. Lemoine]
- ILRS Conventions generally adopted
  - latest SLRF2008 coordinates; fixed to a priori values
  - IERS C04 EOPs used; fixed to a priori values
  - Strict adherence to ILRS Data Handling file
  - Tropo correction model: Mendez and Pavlis (2004)
  - Elevation angle cutoff: 12 degs
  - Thermal drag modeled
  - MSIS static atmosphere neutral density model
- Processed using 1-day data arcs
- Estimated parameters per data arc
  - SpinSat orbit state (X,Y,Z) and (Vx,Vy,Vz)
  - Atmospheric drag at 6hr intervals; adjacent parameters constrained (σ = 0.1)
  - Along-track constant acceleration

Large RMS differences in Fig. C.1. due to modeling during periods of low observation volume. Will investigate impacts from dVs and potential benefits of adding SSN obs.

Orbit overlaps (Fig. C.1.) – overall RMS = 85.4 (± 72.6) meters

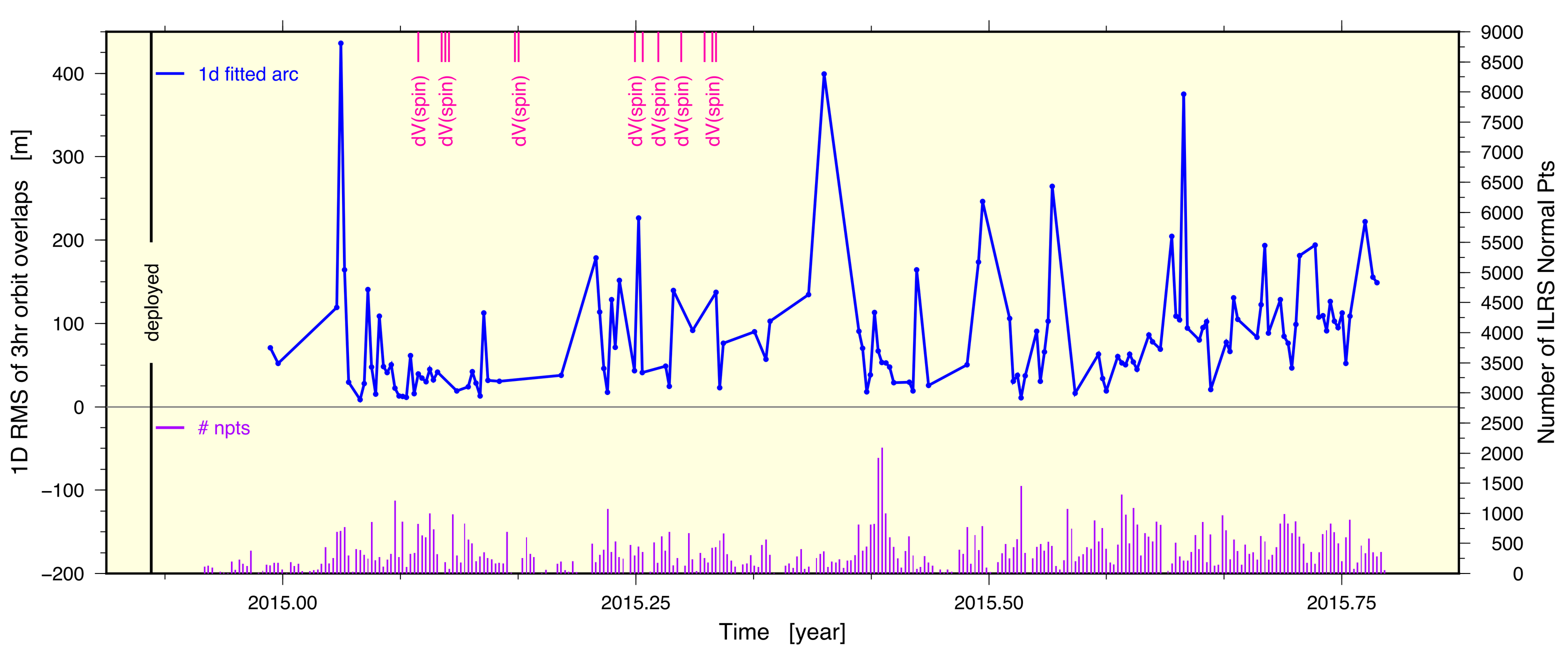


Figure C.1. In blue, 1D RMS statistics from 3hr orbit overlap comparisons of predicted and observed satellite positions between successive days. Gaps in the RMS time series are caused by sparse tracking periods. The violet vertical bars are from Fig. B.1. and indicate the daily number of SLR observations.

Atmospheric Drag — D

The limiting error source in determining the dynamical orbit of a spacecraft at altitudes below 1000 km is in modeling the acceleration due to atmospheric drag, that is, C_d in:

$$a = -\frac{1}{2}\frac{C_d A}{m}\rho v^2$$

where a is the acceleration due to drag, A is the projected frontal surface area of the satellite, m is the satellite mass, ρ is the atmospheric density, v is the satellite velocity relative to the medium.

The effect of atmospheric drag grows exponentially with decreasing satellite altitude. Temporal variations in C_d are typically well-correlated with changes in solar activity.

SpinSat was deployed into a ~51.6° inclined, nearly circular orbit at an altitude of ~425 km. Today, it is at ~377 km altitude and is expected to decay in May 2016.

Fig. D.1. shows time series of SpinSat C_d estimates and the F10.7 cm radio flux as a proxy for solar activity. The general trend and periodic departures in C_d generally follow solar activity. Though, the response in C_d appears exaggerated during some periods of higher solar activity. This could be caused by under-sampling of the orbit. We will investigate the potential benefits of adding SSN observations.

Overall, the average C_d = 1.90 ± 0.59

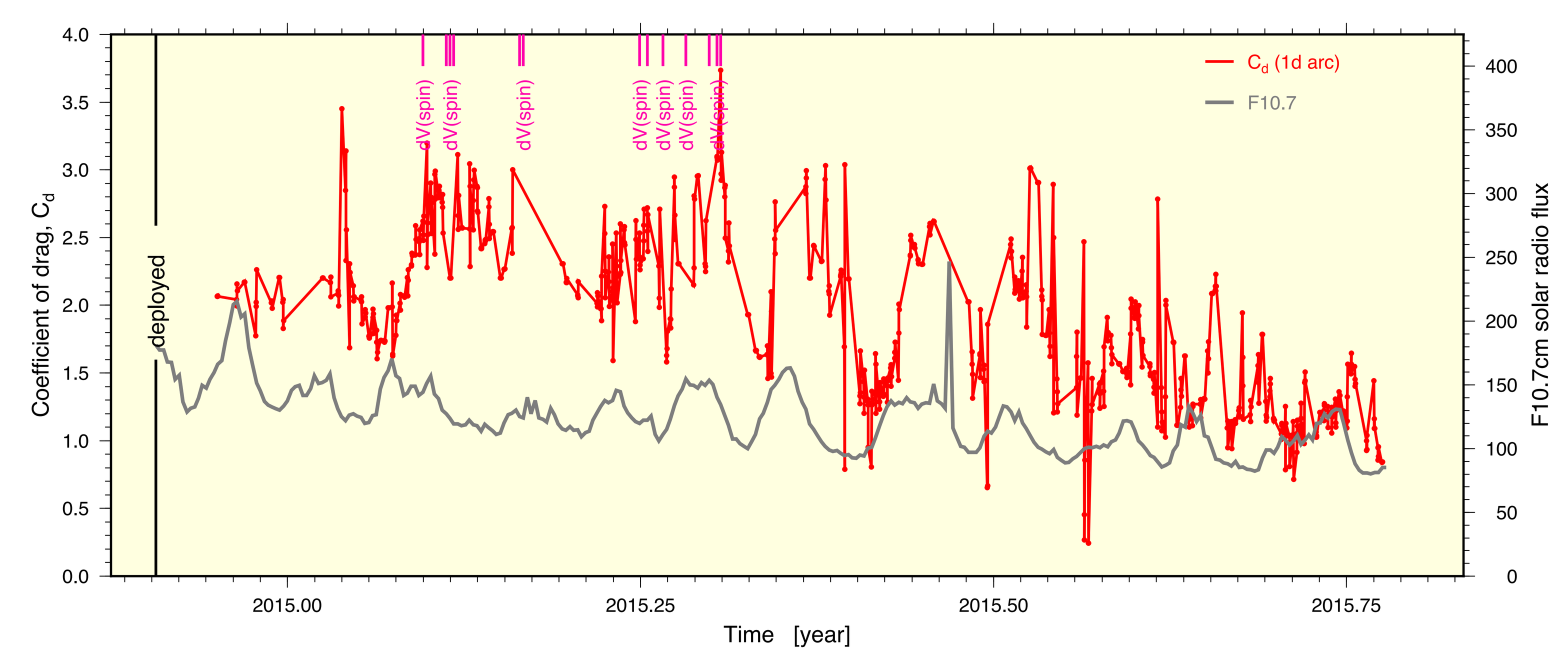


Figure D.1. In red, time series of drag coefficients, C_d, for SpinSat, estimated every 6hr using daily data spans. The black curve is for solar radio flux at 10.7 cm wavelengths; it is plotted here as an indicator of solar activity. Gaps in the C_d time series are caused by having too few SLR observations for the day.

Spin Rate and Attitude — E

The spin determination method is based on the analysis of kHz range residuals (e.g. Fig. E.1.—black dots). For a high return-rate pass, the leading edge of the residuals can be identified (Fig. E.1. – red dots), along with the tracks given by the returns from individual corner cube retro-reflectors (Fig. E.2.).

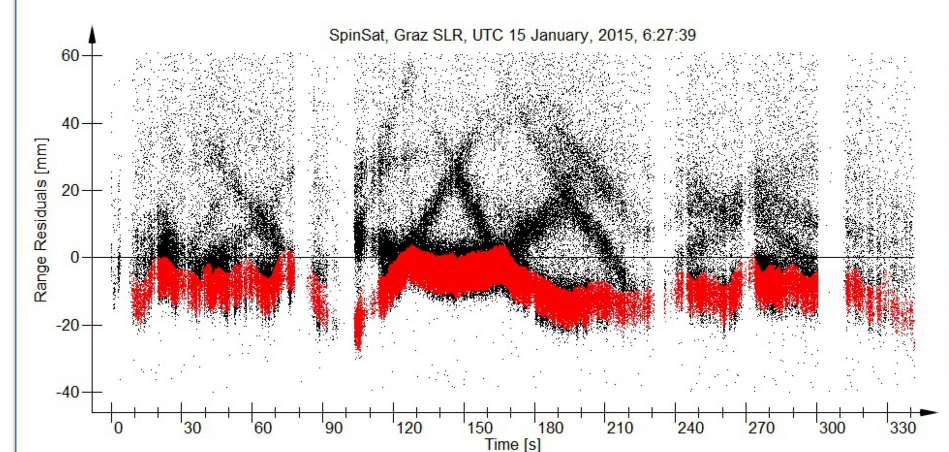


Figure E.1. Time series of 2kHz SLR residuals from Graz for a pass on 15 Jan 2015. Orbit dynamics have been removed. The parabolic features are for individual corner cubes passing through the field-of-view. The red markers indicate the leading edge of the satellite laser retroreflector array.

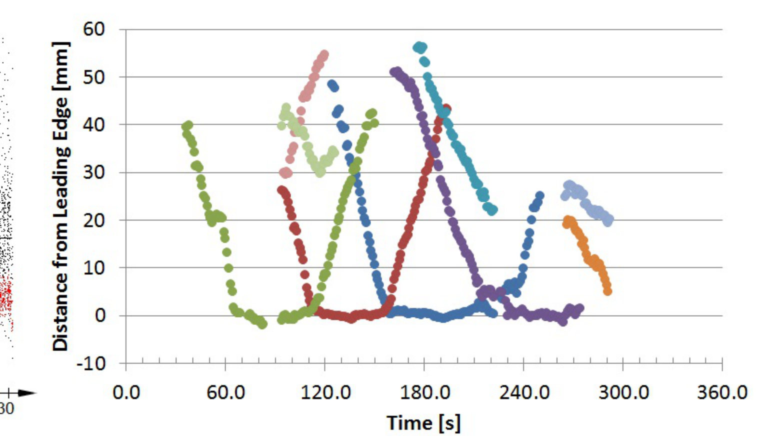


Figure E.2. Tracks of individual corner cubes observed in Fig. E.1.

To identify the spin parameters (spin axis orientation and spin period), synthetic patterns are compared to observed residuals (see Fig. E.1.). For the synthetic patterns, it is assumed that the satellite spins about its symmetry axis, and the spin parameters do not change during a single pass. For this analysis:

- spin axis orientation – 6506 orientations separated by an angle of 3°
- spin period – 122 spin periods, incrementally increased from 300s to 1000s
- spin phase – 360 steps w/ 1° steps

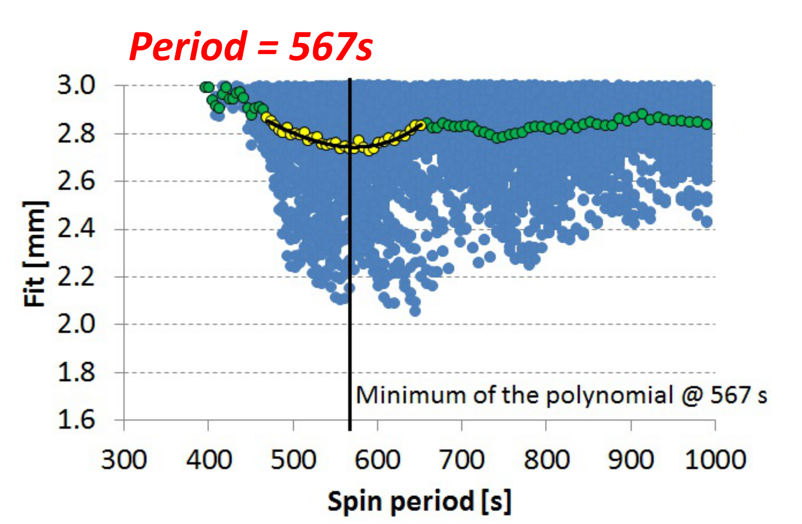


Figure E.3. Blue are all fitted parameters between observed and simulated patterns. Green are average values for each spin period. Yellow is selected part of polynomial for spin period approximation.

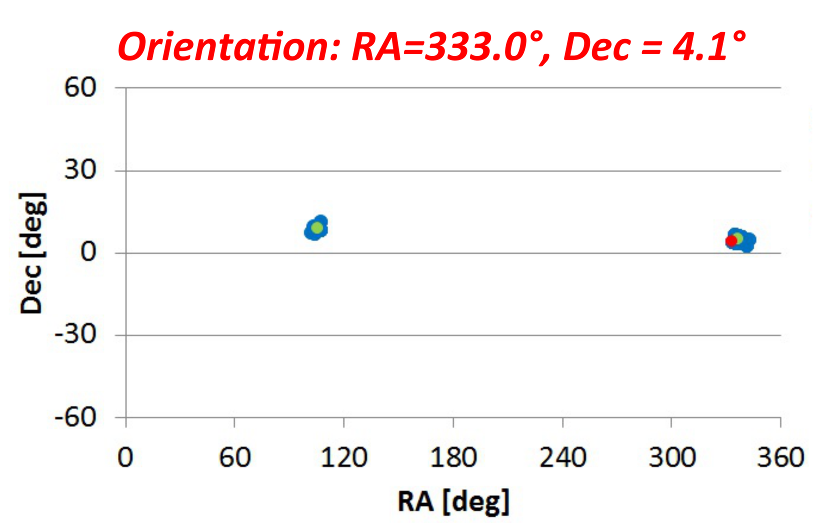


Figure E.4. Blue are fit parameters for spin period of 567s. Green is mean of the fit parameters. Red is best fit parameter (2.15 mm).