Exhibit C: LeoLabs Report
Swarm Technologies Inc.

Trackability and Detectability of the SpaceBEE Satellites

Report prepared for Swarm Technologies by LeoLabs, Inc.
Version 1: October 26, 2018

Summary

In this report, LeoLabs' measurements on 10 resident space objects is summarized. Observations of the 4 SpaceBEE 1/4U satellites are compared with observations on two 1U cubesats launched in similar orbits, two 1/2U satellites orbiting at higher altitudes, and two reference spheres orbiting at higher altitudes.

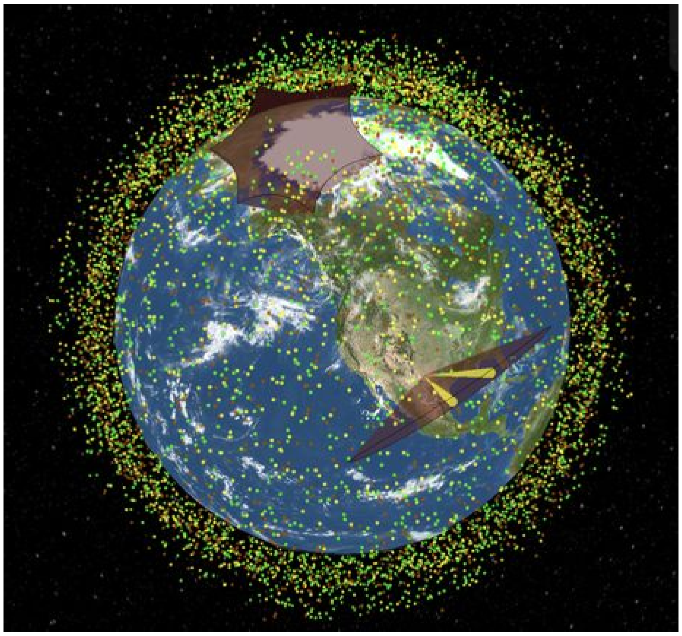
The analysis produced the following findings:

- Trackability was determined by computing the percentage of collected passes versus attempted passes. The SpaceBEEs have similar detection rates as compared to a much larger 1-m^2 reference sphere orbiting at a higher altitude; higher detection rates as compared to the 1U satellites orbiting at similar altitudes; and much higher detection rates as compared to the 1/2U satellites orbiting at a higher altitude.
- The radar cross-section (RCS) of the SpaceBEEs is comparable to or greater than the other cubesats. Of particular note, the RCS of the SpaceBEEs was approximately twice the RCS of one of the 1U satellites.
- The RCS spread of the SpaceBEEs was comparable to, but in some cases higher than the other cubesats. The spread in RCS is estimated to be 50-100%, due to aspect sensitivity of the scattering.
- LeoLabs is able to maintain orbit determination and precision tracking on all objects to roughly the 100-m level (RMS) or better. Roughly 90% of the time, tracking is maintained to better than 1 km at time of estimation (additional uncertainties would be introduced when propagating the states).

Description of LeoLabs Tracking Capabilities

LeoLabs is a Silicon Valley-based startup with a founding team that has over 30 years of experience designing, building, and operating large radar systems and data platforms. LeoLabs was founded to address the need for new sources of tracking data driven by the rapid commercial development of low-Earth orbit (LEO). LeoLabs operates a commercial space situational awareness platform serving the LEO space community, including satellite operators, civil space agencies, SSA organizations, and researchers. LeoLabs builds and operates a proprietary, worldwide network of radars and the cloud-based software platform that turns this radar data into real-time, actionable information. This information is delivered via a RESTful application program interface (API) and a web-based platform, available at https://platform.leolabs.space.

LeoLabs currently utilizes two radar systems to monitor LEO, one near Fairbanks, Alaska and the other near Midland, Texas. These radars continually monitor satellites and debris as they pass overhead. LeoLabs' radars are phased arrays, with no moving parts. They consist of hundreds to thousands of transmit and receive elements, and are operated remotely with no onsite staff. The radars have the ability to track more than 1,000 objects per hour. This high tracking rate is critical for persistently monitoring the entire LEO population of space debris.



Today LeoLabs' network consists of two UHF radars, which regularly track more than 10,000 objects in the LEO public catalog. These radars track objects at inclinations of 30° and higher, and objects that have an equivalent RCS of roughly a 10 cm sphere or larger. They revisit prioritized objects between 1 and 2 times per day on average, and revisit most objects at least once every 1-2 days. Beginning in 2019, LeoLabs will build additional radars, located at sites around the world, that will increase this revisit rate and detect smaller debris.

Observations from the radar systems include high precision range, Doppler, and signal strength, which are used to derive data products such as satellite ephemerides. Radar measurements are automatically calibrated and validated[1]. Ephemerides are provided with calibrated covariances, which are validated using well-tracked objects with known precision ephemerides. RCS is calculated using the measured signal strength along with relevant system parameters, and automatically validated against objects with known and stable RCS.

Targets under Study

The SpaceBEE satellites (NORAD IDs 43142, 43141, 43140, 43139) are 1/4U satellites owned by Swarm Technologies, launched in early 2018 on the PSLV C40 mission. These satellites orbit at roughly 500 km. Their trackability and detectability is the subject of this report.

For the purposes of this study, measurements on the following satellites were used for comparison to the SpaceBEE satellites:

- The Aerocube satellites (NORAD IDs 40045 and 40046). These 1/2U satellites were launched in 2014, and are operated by the Aerospace Corporation. They orbit at roughly 650 km.

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[1] [Nicolls et al., 2017] "Conjunction Assessment for Commercial Satellite Constellations using Commercial Radar Data Sources" in *Advanced Maui Optical and Space Surveillance Technologies Conference*, September 2017.

- The STEP Cube Lab satellite (NORAD ID 43138). This 1U South Korean satellite was launched in early 2018 and orbits at ~500 km. It was deployed on the same PSLV launch as the SpaceBEEs.
- The AO-92 (FOX 1D) satellite (NORAD ID 43137). This 1U AMSAT satellite was launched in early 2018 and orbits at ~500 km. It was deployed on the same PSLV launch as the SpaceBEEs.
- Reference spheres. RIGIDSPHERE-2 (NORAD ID 5398) is a calibration sphere with known 1 m^2 RCS and STELLA (NORAD ID 22824) is a well-tracked 24-cm diameter (a cross sectional area of .045 m^2) laser calibration sphere. Both objects orbit at roughly 800 km.

Measurements Available

Table 1 summarizes the measurements available for the 10 objects under study. The number of attempted passes is affected by a number of factors, including the prioritization level of the object and its orbit, which affects the visibility from LeoLabs' radar sensors. The fact that satellites have a variable number of attempted passes is due to these factors. With LeoLabs' two radar sensors, and with high prioritization, the SpaceBEEs are being tracked on average roughly 1.1-1.2 times per day (fifth column of Table 1).

The detectability of the satellites is determined by the percentage of passes with measurements (fourth column of Table 1). Detectability is influenced by the altitude of the spacecraft, its RCS, and how its RCS varies with time. It is also influenced by the accuracy of the orbital state estimate of the object, which may influence radar pointing, especially for low elevation passes. For these reasons, even a very large, well-tracked object will not be 100% detectable.

Based on the results in Table 1, we find that the detectability of the SpaceBEE satellites is:

- Similar to the much larger 1-m^2 reference sphere, which orbits at higher altitude (resulting in lower SNR);
- Higher than the much larger 24-cm sphere, which orbits at higher altitude (resulting in lower SNR);
- Higher than the 1U satellites (STEP Cube Lab and AO-92) which are in very similar orbits;
- Much higher than the 1/2U Aerocube satellites, which are in a higher altitude orbit.

Measured Radar Cross-section (RCS)

An object's RCS is related to an object's physical area, but refers specifically to the amount of incident power than is reflected back to the transmitter. RCS is typically dependent on the frequency of the radar system as well as material and geometrical properties of the scatterer. Because scattering strength is very often dominated by large, individual scatterers, satellites with appendages or antennas often have a larger RCS than their geometrical size would predict. The opposite could also be true due to destructive interference in the scattering.

Median RCS values for the 10 satellites under study are summarized in Table 2, and distributions of the measurements are plotted in Figure 1. Because RCS varies based on aspect angle, spacecraft attitude, and radar operating frequency, the histograms in Figure 1 are shown for LeoLabs' two radar systems. A combined distribution is also shown. Table 2 also summarizes a measure of the "spread" of the RCS distributions. These values are computed as the difference between the 75th and 25th percentiles of the data (the so-called interquartile range, or IQR).

The RCS of the SpaceBEE satellites is:

- Roughly 0.12 m^2;
- Comparable to one of the 1U cubesats (STEP Cube Lab), and about twice the size of the other 1U cubesat (AO-92);
- Comparable to the 1/2U Aerocube satellites;
- Roughly 7.8 times smaller than the 1-m^2 reference sphere, and roughly 2.4 times smaller than the 24-cm sphere.

The fact that both the SpaceBEE and the Aerocube satellites have comparable and in some cases larger RCS as compared to the 1U satellites speaks to the scattering being dominated by deployables. In particular, the SpaceBEE satellites have a long deployable VHF antenna that likely dominates scattering for LeoLabs' UHF radar systems.

The RCS spread is due to aspect sensitivity in the scattering from the satellites, and can also be influenced by calibration errors in the processing, especially when the SNR is low. The RCS spread of ~42% for the 1-m^2 sphere is due to variations in gain and system calibration, as this object would be expected to have a very stable and constant RCS. The cubesats exhibit a much larger spread (close to 100%) which is due to the aspect sensitivity of the target. Taking into account the calibration errors, we see that the spread in RCS is ~50-60% for most of the cubesats. The SpaceBEEs have a somewhat larger spread than the other cubesats, likely due to its small body size and long deployable antenna, which results in anisotropy in the scattering process.

Orbital Solution Accuracy

When LeoLabs collects sufficient measurements on a given satellite, it uses those measurements to estimate an orbital state. The orbit determination procedure returns a covariance that can be used to assess the uncertainties in the orbital state. This uncertainty represents the error in the position and velocity of the satellite, and can be propagated forward in time with the state itself. The uncertainty and its evolution in time is extremely important for safety-of-flight, in particular for predicting close approaches that have high probability-of-collision. LeoLabs uses automated validation and calibration to ensure that its covariances accurately represent the uncertainties in the state of the satellites.

Table 3 summarizes the orbit determination results for the 10 satellites under study, aggregated over 2018 and also summarized for the period since September 2018. Parameters in the table are derived from the histograms of the state uncertainties shown in Figure 2. Various quantities can influence the quality of orbit determination, including measurement availability and uncertainties as well as orbit dynamics. In particular, the largest source of error is caused by unpredicted variations in atmospheric drag. Satellites orbiting at lower altitude are subject to larger drag forces and thus in general have worse orbit specifications. In addition, small satellites with high area-to-mass ratios are more influenced by drag.

As shown in Table 3, LeoLabs produces states on the SpaceBEE satellites with a typical uncertainty of 60-120 meters. This is comparable to the Aerocube satellites, and slightly worse than the 1U satellites, likely due to unmodeled drag forces and a higher area-to-mass ratio. However, with prioritized tracking, LeoLabs is able to estimate states on the SpaceBEEs to better than 1 km accuracy roughly 95% of the time. 50-70% of the time, these state estimates are better than 100 meters.

Table 1. Summary of detection rates for the objects under study. Data from 2018 up to 10/24/2018 was included in this analysis.

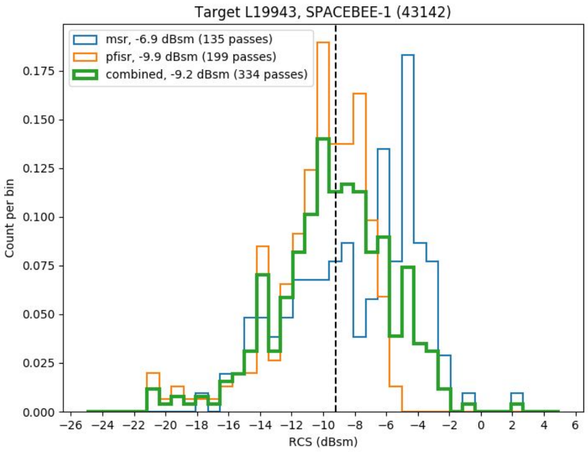
Satellite	Number of Attempted Passes	Number of Passes with Detections	Percentage of Passes with Detections	Detection Rate
SpaceBEE-1 (43142)	478	334	~70%	~1.1/day
SpaceBEE-2 (43141)	464	329	~71%	~1.1/day
SpaceBEE-3 (43140)	459	344	~75%	~1.2/day
SpaceBEE-4 (43139)	466	343	~74%	~1.2/day
STEP Cube Lab (43138)	398	265	~67%	~0.9/day
AO-92 (43137)	409	238	~58%	~0.8/day
Aerocube-6A (40045)	383	168	~44%	~0.6/day
Aerocube-6B (40046)	391	187	~48%	~0.6/day
Rigidsphere-2 (5398)	536	388	~72%	~1.3/day
Stella (22824)	594	377	~63%	~1.3/day

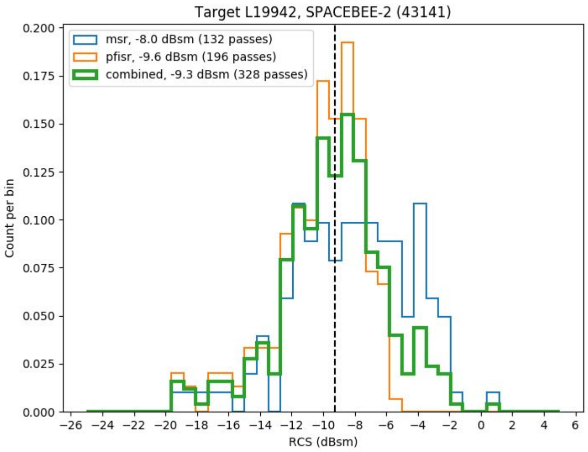
Table 2. Summary of RCS values in dBsm and m^2, along with RCS distribution spread (computed as the interquartile range of the data). Data from 2018 up to 10/24/2018 was included in this analysis.

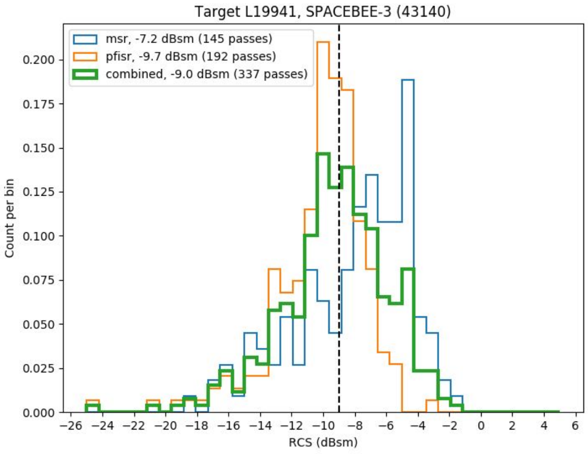
Satellite	Median RCS (dBsm)	Median RCS (m^2)	RCS Spread (m^2)
SpaceBEE-1 (43142)	-9.2 dBsm	0.12 m^2	0.14 m^2(114%)
SpaceBEE-2 (43141)	-9.3 dBsm	0.12 m^2	0.10 m^2 (88%)
SpaceBEE-3 (43140)	-9.0 dBsm	0.13 m^2	0.12 m^2 (95%)
SpaceBEE-4 (43139)	-9.6 dBsm	0.11 m^2	0.13 m^2 (115%)
STEP Cube Lab (43138)	-10.2 dBsm	0.10 m^2	0.06 m^2 (66%)
AO-92 (43137)	-13.3 dBsm	0.05 m^2	0.06 m^2 (136%)
Aerocube-6A (40045)	-9.6 dBsm	0.11 m^2	0.08 m^2 (74%)
Aerocube-6B (40046)	-8.4 dBsm	0.14 m^2	0.12 m^2 (85%)
Rigidsphere-2 (5398)	-0.2 dBsm	0.94 m^2	0.40 m^2 (42%)
Stella (22824)	-4.1 dBsm	0.39 m^2	0.25 m^2 (64%)

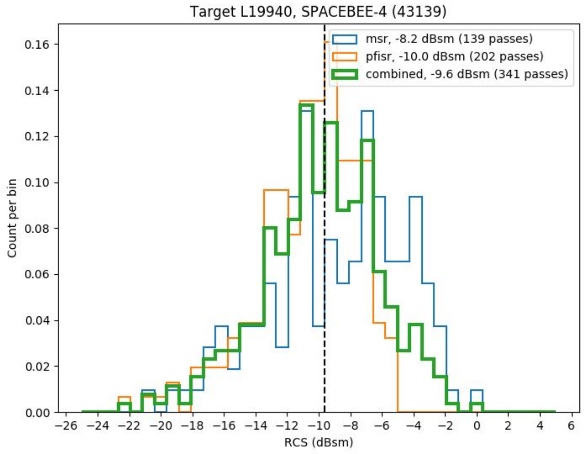
Table 3. Summary of RMS uncertainties for LeoLabs orbit determination. Data from 2018 up to 10/24/2018 was included in this analysis. Values are reported at the epoch of the orbit determination.

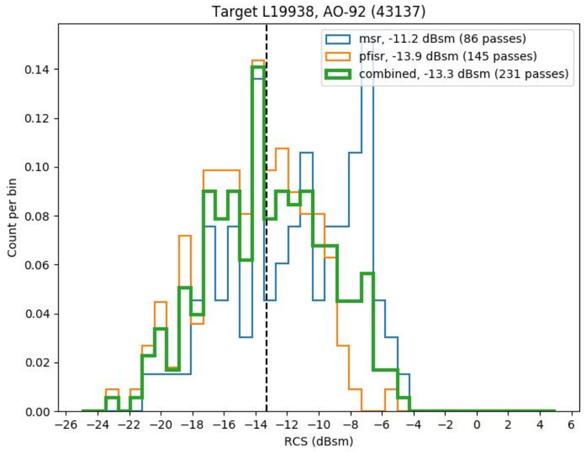
Satellite	Median RMS Error 9/1/2018 to 10/24/2018	Median RMS Error YTD	%<1 km RMS YTD	%<100 m RMS YTD
SpaceBEE-1 (43142)	132.0 m	120.4 m	83.3%	48.1%
SpaceBEE-2 (43141)	81.7 m	78.4 m	91.8%	59.0%
SpaceBEE-3 (43140)	40.0 m	66.0 m	96.9%	62.5%
SpaceBEE-4 (43139)	77.6 m	60.0 m	95.4%	70.8%
STEP Cube Lab (43138)	40.5 m	57.8 m	89.6%	68.8%
AO-92 (43137)	48.2 m	72.7 m	87.1%	54.8%
Aerocube-6A (40045)	54.6 m	104.0 m	88.6%	47.7%
Aerocube-6B (40046)	45.5 m	60.2 m	94.2%	67.3%
Rigidsphere-2 (5398)	22.5 m	27.8 m	100.0%	93.6%
Stella (22824)	45.5 m	44.0 m	100.0%	85.9%

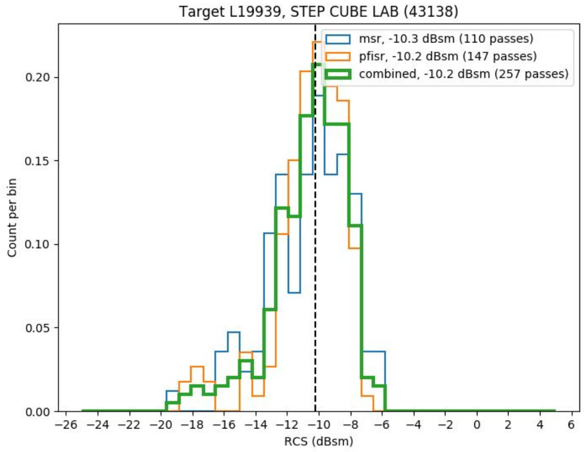

Target L19943, SPACEBEE-1 (43142)
msr, -6.9 dBsm (135 passes)
pfisr, -9.9 dBsm (199 passes)
combined, -9.2 dBsm (334 passes)
Count per bin
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
−26 −24 −22 −20 −18 −16 −14 −12 −10 −8 −6 −4 −2 0 2 4 6
RCS (dBsm)


Target L19942, SPACEBEE-2 (43141)
msr, -8.0 dBsm (132 passes)
pfisr, -9.6 dBsm (196 passes)
combined, -9.3 dBsm (328 passes)
Count per bin
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
−26 −24 −22 −20 −18 −16 −14 −12 −10 −8 −6 −4 −2 0 2 4 6
RCS (dBsm)


Target L19941, SPACEBEE-3 (43140)
msr, -7.2 dBsm (145 passes)
pfisr, -9.7 dBsm (192 passes)
combined, -9.0 dBsm (337 passes)
Count per bin
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
−26 −24 −22 −20 −18 −16 −14 −12 −10 −8 −6 −4 −2 0 2 4 6
RCS (dBsm)


Target L19940, SPACEBEE-4 (43139)
msr, -8.2 dBsm (139 passes)
pfisr, -10.0 dBsm (202 passes)
combined, -9.6 dBsm (341 passes)
Count per bin
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
−26 −24 −22 −20 −18 −16 −14 −12 −10 −8 −6 −4 −2 0 2 4 6
RCS (dBsm)


Target L19938, AO-92 (43137)
msr, -11.2 dBsm (86 passes)
pfisr, -13.9 dBsm (145 passes)
combined, -13.3 dBsm (231 passes)
Count per bin
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
−26 −24 −22 −20 −18 −16 −14 −12 −10 −8 −6 −4 −2 0 2 4 6
RCS (dBsm)


Target L19939, STEP CUBE LAB (43138)
msr, -10.3 dBsm (110 passes)
pfisr, -10.2 dBsm (147 passes)
combined, -10.2 dBsm (257 passes)
Count per bin
0.00
0.05
0.10
0.15
0.20
−26 −24 −22 −20 −18 −16 −14 −12 −10 −8 −6 −4 −2 0 2 4 6
RCS (dBsm)

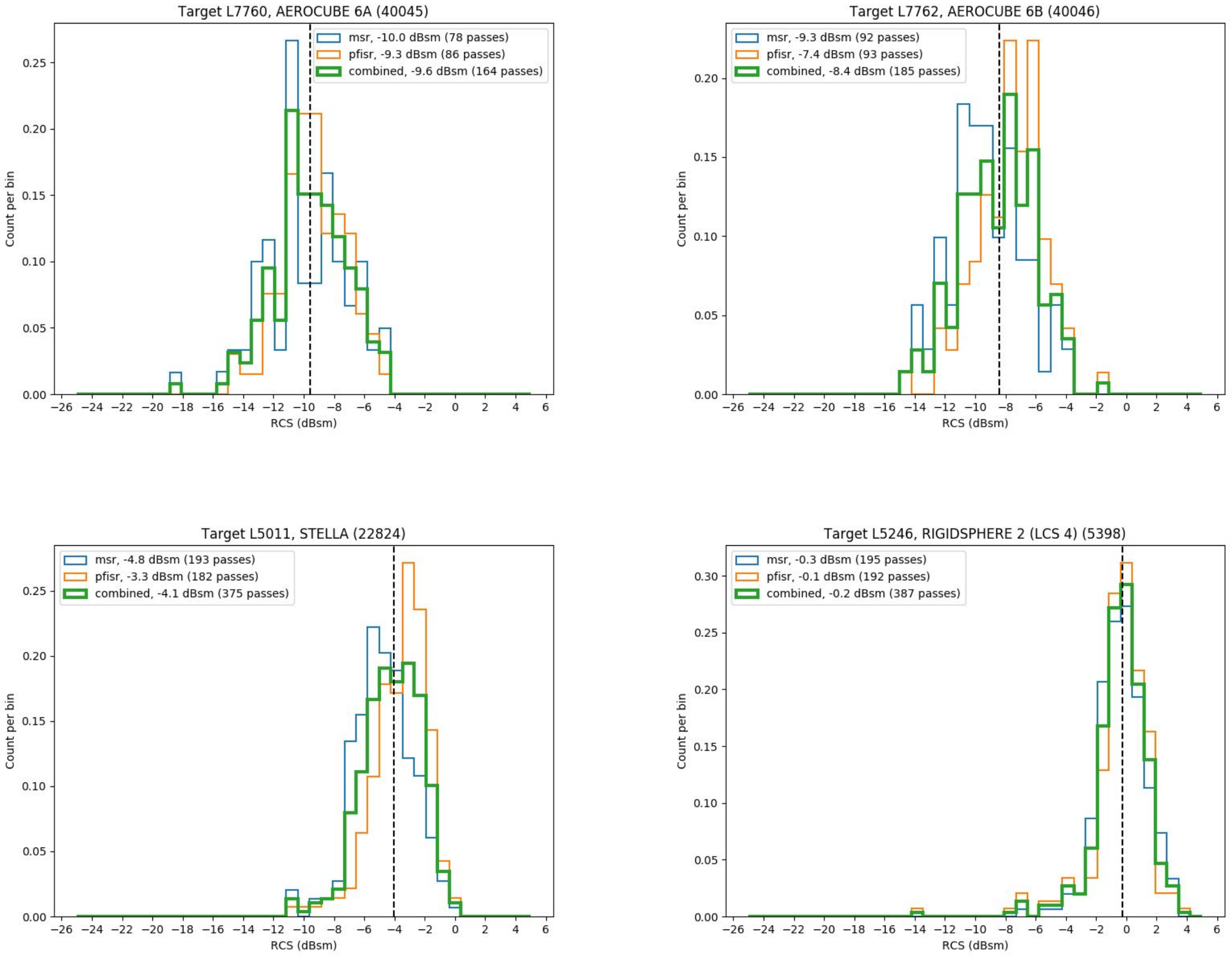
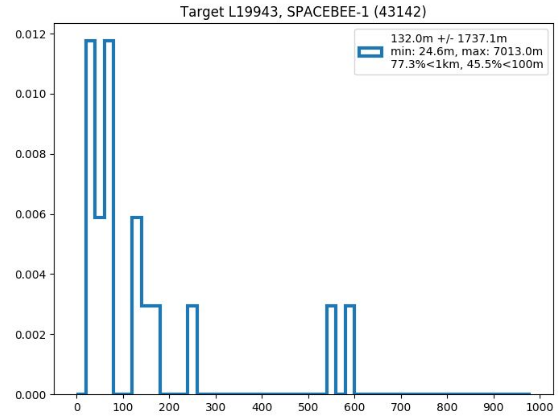
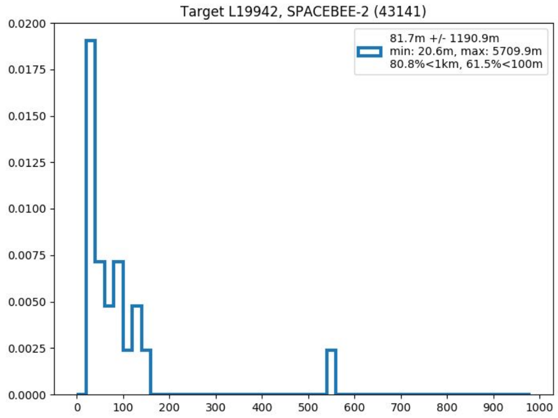
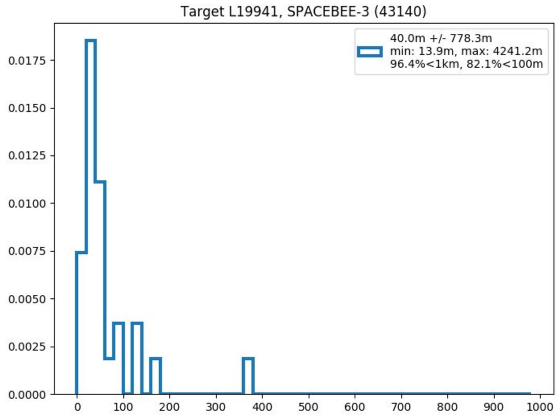
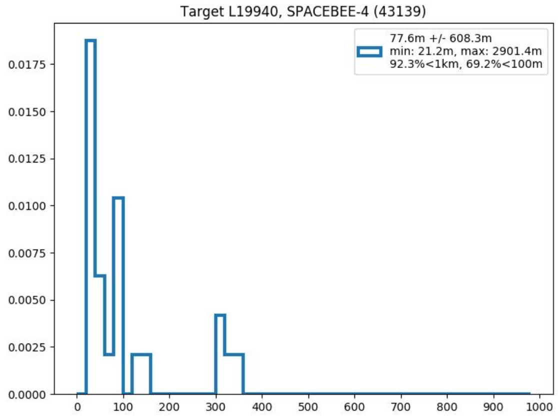


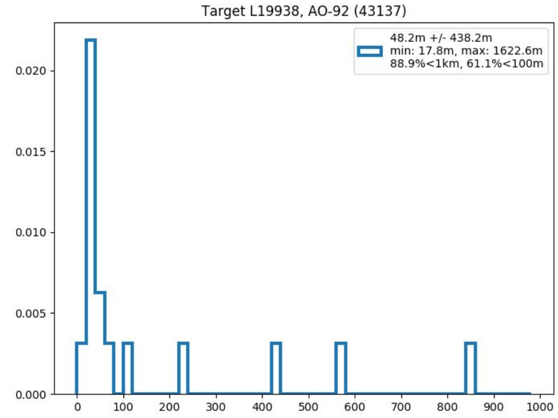
Figure 1. Histograms of RCS measurements for the 10 objects under study.

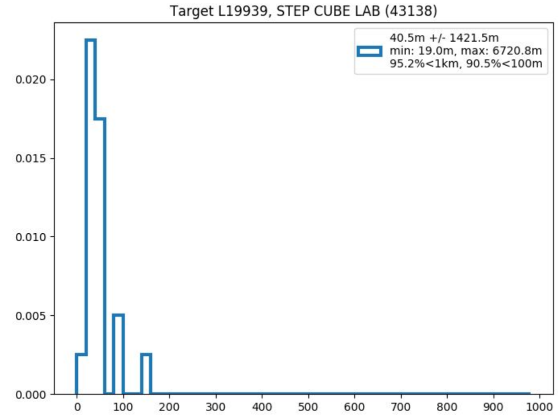

Target L19943, SPACEBEE-1 (43142)
132.0m +/- 1737.1m
min: 24.6m, max: 7013.0m
77.3%<1km, 45.5%<100m
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
100
200
300
400
500
600
700
800
900
1000


Target L19942, SPACEBEE-2 (43141)
81.7m +/- 1190.9m
min: 20.6m, max: 5709.9m
80.8%<1km, 61.5%<100m
0.0200
0.0175
0.0150
0.0125
0.0100
0.0075
0.0050
0.0025
0.0000
0
100
200
300
400
500
600
700
800
900
1000


Target L19941, SPACEBEE-3 (43140)
40.0m +/- 778.3m
min: 13.9m, max: 4241.2m
96.4%<1km, 82.1%<100m
0.0175
0.0150
0.0125
0.0100
0.0075
0.0050
0.0025
0.0000
0
100
200
300
400
500
600
700
800
900
1000


Target L19940, SPACEBEE-4 (43139)
77.6m +/- 608.3m
min: 21.2m, max: 2901.4m
92.3%<1km, 69.2%<100m
0.0175
0.0150
0.0125
0.0100
0.0075
0.0050
0.0025
0.0000
0
100
200
300
400
500
600
700
800
900
1000


Target L19938, AO-92 (43137)
48.2m +/- 438.2m
min: 17.8m, max: 1622.6m
88.9%<1km, 61.1%<100m
0.020
0.015
0.010
0.005
0.000
0
100
200
300
400
500
600
700
800
900
1000


Target L19939, STEP CUBE LAB (43138)
40.5m +/- 1421.5m
min: 19.0m, max: 6720.8m
95.2%<1km, 90.5%<100m
0.020
0.015
0.010
0.005
0.000
0
100
200
300
400
500
600
700
800
900
1000

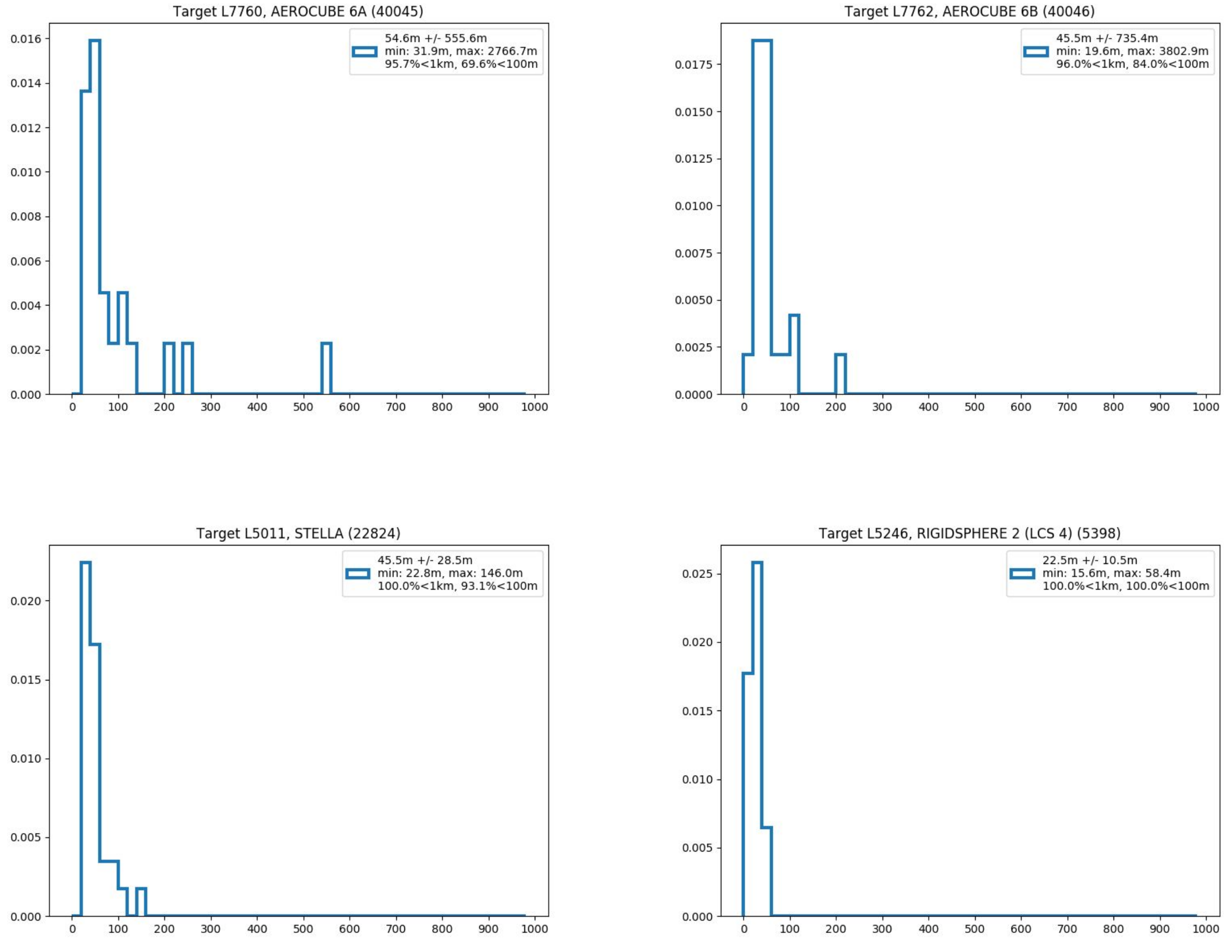


Figure 2. Histograms of RMS state uncertainties at epoch for the 10 objects under study.