Trackability and Detectability of PocketQube Satellites

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Summary

In this report, LeoLabs' measurements on 12 resident space objects are summarized. Observations of four previously launched PocketQube satellites with 1P, 1.5P, and 2.5P form factors are compared with observations of two 1/4U cubesats, two 1/2U satellites, two 1U cubesats, and two reference spheres. The PocketQube form factors include one satellite with a 1P form factor, two satellites with a 1.5P form factor, and one satellite with a 2.5P form factor.

The analysis produced the following findings:

- Trackability was determined by computing the percentage of collected passes versus attempted passes. The 1P PocketQube and one of the 1.5P PocketQubes had similar detection rates to the 1/2U cubesats orbiting at slightly higher altitudes. They also had similar detection rates to one of the 1U cubesats orbiting at a lower altitude. The other two PocketQubes (1.5P and 2.5P form factors) had lower detection rates, however could still be regularly detected by LeoLabs radar sensors.
- The radar cross-section (RCS) varied considerably amongst the PocketQube satellites. For the two with the higher detection rates, the median RCS measured by LeoLabs was about 0.06 m^2, which is comparable or slightly larger than one of the 1U cubesats studied, and about half the RCS of the 1/4U and 1/2U cubesats. The PocketQubes with the lower detection rates (1.5P and 2.5P form factors) had median RCS values of 0.01-0.02 m^2, which is 5-10 times lower than the other satellites investigated. Note that an RCS value of 0.01 m^2 is roughly equivalent to an 11-cm diameter sphere in the optical scattering regime.
- The RCS spread of the PocketQubes was comparable to the other small satellites. The spread in RCS is estimated to be 80-100%, likely due to aspect sensitivity of the scattering as well as statistical uncertainty in the measurements.
- A detailed investigation of the orbit determination performance on the PocketQubes was not performed, as there was insufficient data at the time of report creation. However, for the 1P PocketQube, which is fairly well tracked by LeoLabs, it was found that orbit determination performance was better than the 1-km level (RMS) at epoch roughly 66% of the time. Note that additional uncertainties would be introduced when propagating the states.
- With prioritized, well-tracked objects, LeoLabs sees orbit determination performance at the 1-km level (RMS) close to 100% of the time, and it is expected that with additional tracking such performance could be achieved on the PocketQube satellites.

The specific purpose of this report is to understand the likely detectability of PocketQube satellites of various form factors (1P, 2P, 3P) to be placed into sun-synchronous orbit (SSO) at approximately 400

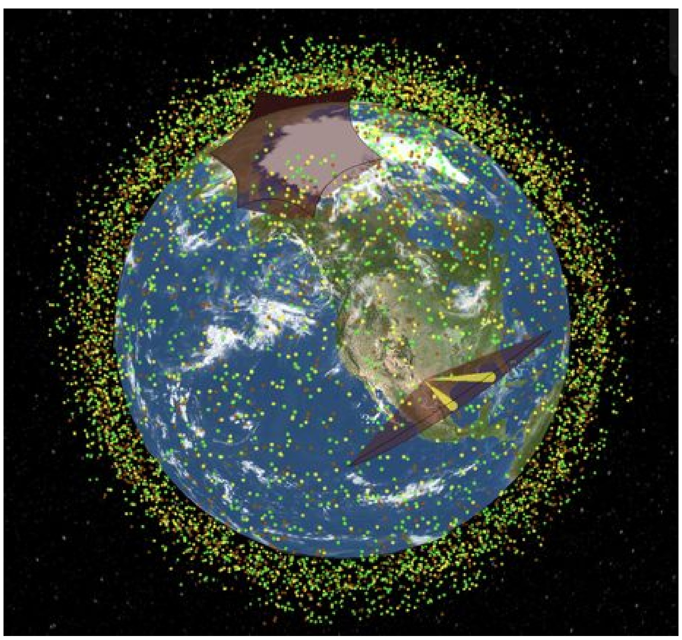
km. The above findings indicate that PocketQube satellites, even down to 1P form factors, can have similar detection statistics as 1/4U, 1/2U, and even 1U cubesats. However, they generally have lower RCS values than these other form factors, although we emphasize that the on-orbit RCS is often a strong function of the deployed structures from the satellites. A detailed investigation of the RCS for the PocketQubes given their deployable structures was not conducted.

Given that all four PocketQubes studied were at altitudes >550 km and trackable by LeoLabs sensors, the 1P, 2P, and 3P PocketQubes at 400 km and below are very likely to be trackable by LeoLabs sensors, especially if they plan to deploy antennas, solar panels, or other metallic deployable structures. However, because the detection rates are lower than other platforms, it is advisable that these objects are prioritized for tracking and their orbit determination performance carefully assessed and monitored over the satellite lifetime.

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^{o} 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. The first of these new radar sensors was recently completed in New Zealand and will begin flowing data into LeoLabs' production system in early 2020.

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

[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.

signal strength along with relevant system parameters, and automatically validated against objects with known and stable RCS.

Targets under Study

Table 1 summarizes the objects studied for this report. Four previously launched PocketQube satellites were investigated (NORAD IDs 39434, 39436, 39437, and 39443). These satellites consist of:

- The Dove-4 PocketQube, which has a 1P (5 cm x 5 cm x 5 cm) form factor. Note that according to the NORAD catalog at space-track.org, this satellite is a 3U cubesat launched by Planet Labs (formerly Cosmogia). However, it was reported by Alba Orbital that this is actually the 1P REN PocketQube. This was not independently verified by LeoLabs, and conclusions pertaining to this satellite would be affected by this information given that a 3U cubesat has a much larger form factor.
- The $50Sat PocketQube, which has a 1.5P (5 cm x 5 cm x 8 cm) form factor. This satellite re-entered in 2018.
- The Beakersat-1 PocketQube, which also has a 1.5P form factor. This satellite re-entered in early 2019.
- The QubeScout-S1 PocketQube, which has a 2.5P (5 cm x 5 cm x 12 cm) form factor.

Note that all four PocketQubes orbit (or orbited prior to re-entry) at an altitude of about 600 km.

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

- Two SpaceBEE satellites (NORAD IDs 43141 and 43142). These 1/4U satellites owned by Swarm Technologies were launched in early 2018 on the PSLV C40 mission. They orbit at roughly 500 km.
- 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.
- The STEP Cube Lab satellite (NORAD ID 43138). This 1U South Korean satellite was launched in early 2018 and orbits at about 500 km.
- The AO-92 (FOX 1D) satellite (NORAD ID 43137). This 1U AMSAT satellite was launched in early 2018 and orbits at about 500 km.
- 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 2 summarizes the measurements available for the 12 objects under study. The number of attempted passes, shown in the second column, 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.

The PocketQubes under study were not prioritized for data collection, so they were attempted less often than the other satellites. One of the PocketQubes ($50Sat) deorbited in May 2018, so there was less data available on this satellite. The tracking rates of the PocketQube satellites, shown in the fifth column of Table 2, varied from about 0.1 times per day to 0.7 times per day. By comparison, with LeoLabs' two radar sensors and with high prioritization, the 1/4U SpaceBEE satellites are able to be tracked on average roughly 1.1-1.2 times per day (fifth column of Table 1). It is expected that LeoLabs could achieve a higher tracking rate on the PocketQubes after prioritization. In addition, as LeoLabs adds more sensors, the tracking rates will increase.

The detectability of the satellites is determined by the percentage of passes with measurements (fourth column of Table 2). 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 detectable for all attempted passes.

Based on the results in Table 1, we find that the detectability of the PocketQube satellites varies considerably based on the satellite. For the 1P PocketQube (Dove-4) and one of the 1.5P PocketQubes (Beakersat-1), we find that:

- The satellites are detectable 50-60% of the time;
- Their detectability is similar to one of the 1U cubesats (AO-92) orbiting at a lower altitude;
- Their detectability is similar to the two 1/2U Aerocube satellites orbiting at a higher altitude;
- Ther detectability is less than the 1/4U cubesats, the other 1U cubesats, and the reference objects.

For the 2.5P PocketQube (QubeScout-S1), we find that the detectability is about half that of the Aerocube 1/2U cubesats and the AO-92 1U cubesat. For the other 1.5P PocketQube ($50Sat), we find that the detectability is about a third of the Aerocube 1/2U cubesats and the AO-92 1U cubesat. Note that less observations were available for $50Sat, which may have affected the statistics of the results.

Measured Radar Cross-section (RCS)

An object's RCS is related to an object's physical area, but refers specifically to the ability of a target to reflect incident power back to the radar receiver. 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 12 satellites under study are summarized in Table 3, 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 3 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 PocketQube satellites correlates with the detectability statistics outlined in Table 2. For the two PocketQubes with higher detection rates (Dove-4 and Beakersat-1), we find that the RCS is:

- Roughly 0.06 m^2;
- Comparable to one of the 1U cubesats (AO-92), and about two-thirds that of the other 1U cubesat (STEP Cube Lab);
- Roughly half the value of the two SpaceBEE 1/4U satellites and the two 1/2U Aerocube satellites;
- Roughly 16 times smaller than the 1-m^2 reference sphere, and roughly 5 times smaller than the 24-cm sphere.

The RCS of the PocketQube satellites with the lower detection rates ($50SAT and QubeScout-S1) is

- Around 0.01 and 0.02 m^2, which is comparable to the optical cross-section of an 11- and 16-cm diameter sphere, respectively;
- Three to six times smaller than the other PocketQubes;
- Five to ten times smaller than the cubesats studied;
- Roughly 50 and 100 times smaller than the 1-m^2 reference sphere, and roughly 15 and 30 times smaller than the 24-cm sphere.

While the RCS is correlated with the detectability, we observe that there is significant variability in RCS amongst different satellites that is often not correlated with the size of the platform. For example, we might naively expect that the 1U cubesats would have the largest RCS of the satellites studied (not including the reference spheres), however the RCS of one of them is in fact lower than the 1/4U and 1/2U cubesats and is comparable to the RCS of two of the PocketQubes. In addition, the largest PocketQube (QubeScout-S1) in fact has the third lowest RCS of the four studied. This speaks to the scattering being dominated by deployables.

The RCS spread is due to aspect sensitivity in the scattering from the satellites, and can also be influenced by calibration and statistical errors in the processing, especially when the SNR is low. The RCS spread of ~46% 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 PocketQubes and 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 satellites. This variation is likely due to anisotropy in the scattering process for these small systems.

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 4 summarizes the orbit determination results for the 12 satellites under study, aggregated over 2019. 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.

It was not possible with the data available to do a complete analysis on the orbit determination fidelity of the PocketQubes. In general, with prioritized tracking, LeoLabs is able to estimate states on the 1/4U, 1/2U, and 1U satellites to better than 1 km accuracy greater than 95% of the time, and to better than 100 m 30-40% of the time. For the 1P and 2.5P PocketQubes, LeoLabs is able to estimate states to better than 1 km better than 66% of the time and 34% of the time, respectively. Data was not available for the other two PocketQubes since they had deorbited. It is expected that with prioritization and the resulting increased tracking rates performance would improve.

Table 1. A summary of the targets under study.

Satellite	Status	Nominal Perigee/Apogee/ Inclination	Rough Form-Factor
Dove-4 (39434)	In-orbit (2013)	528 km / 573 km / 98°	5 cm x 5 cm x 5 cm (1P) PocketQube ***
$50SAT (39436)	Re-entered (2018)	590 km / 639 km / 98°	5 cm x 5 cm x 8 cm (1.5P) PocketQube
BeakerSat-1 (39437)	Re-entered (2019)	590 km / 639 km / 98°	5 cm x 5 cm x 8 cm (1.5P) PocketQube
QubeScout-S1 (39443)	In-orbit (2013)	563 km / 598 km / 98°	5 cm x 5 cm x 12 cm (2.5P) PocketQube
SpaceBEE-1 (43142)	In-orbit (2018)	479 km / 492 km / 97°	2.5 cm x 10 cm x 10 cm (1/4U) CubeSat
SpaceBEE-2 (43141)	In-orbit (2018)	480 km / 493 km / 97°	2.5 cm x 10 cm x 10 cm (1/4U) CubeSat
STEP Cube Lab (43138)	In-orbit (2018)	485 km / 499 km / 97°	10 cm x 10 cm 10 cm (1U) CubeSat
AO-92 (43137)	In-orbit (2018)	487 km / 502 km / 97°	10 cm x 10 cm 10 cm (1U) CubeSat
Aerocube-6A (40045)	In-orbit (2014)	604 km / 684 km / 98°	5 cm x 10 cm x 10 cm (1/2U) CubeSat
Aerocube-6B (40046)	In-orbit (2014)	604 km / 683 km / 98°	5 cm x 10 cm x 10 cm CubeSat
Rigidsphere-2 (5398)	In-orbit (1971)	735 km / 823 km / 88°	1.12-m diameter sphere
Stella (22824)	In-Orbit (1993)	796 km/ 805 km / 99°	24-cm diameter sphere

***** As reported by Alba Orbital - see text for details.**

Table 2. Summary of detection and tracking rates for the objects under study. Data from 1/1/2018 through 11/25/2019 were included in this analysis.

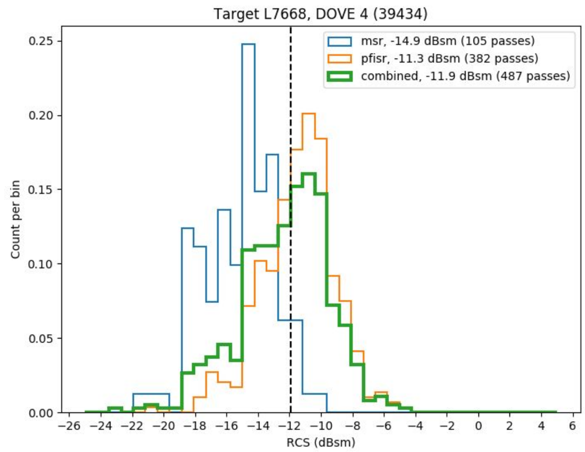
Satellite	Number of Attempted Passes	Number of Passes with Detections	Percentage of Passes with Detections	Tracking Rate
Dove-4 (39434)	978	488	~50%	~0.71/day
$50SAT (39436)	97	16	~17%	~0.11/day
BeakerSat-1 (39437)	373	215	~58%	~0.53/day
QubeScout-S1 (39443)	1017	278	~27%	~0.40/day
SpaceBEE-1 (43142)	1154	858	~74%	~1.27/day
SpaceBEE-2 (43141)	1138	834	~73%	~1.24/day
STEP Cube Lab (43138)	1061	749	~71%	~1.11/day
AO-92 (43137)	1057	638	~60%	~0.94/day
Aerocube-6A (40045)	1068	563	~53%	~0.81/day
Aerocube-6B (40046)	1077	587	~55%	~0.85/day
Rigidsphere-2 (5398)	1229	894	~73%	~1.29/day
Stella (22824)	1359	850	~63%	~1.23/day

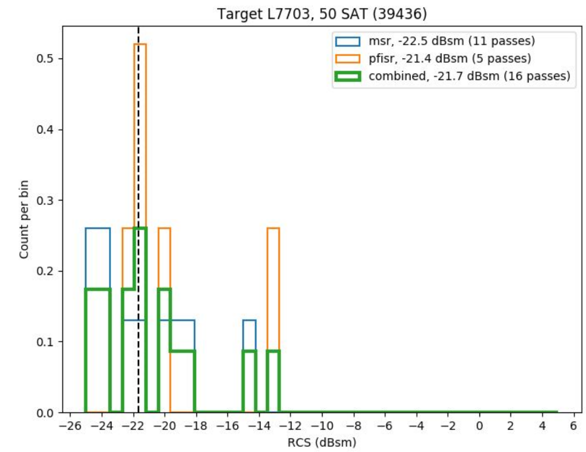
Table 3. Summary of RCS values in dBsm and m^2, along with RCS distribution spread (computed as the interquartile range of the data). Data from 1/1/2018 through 11/25/2019 were included in this analysis.

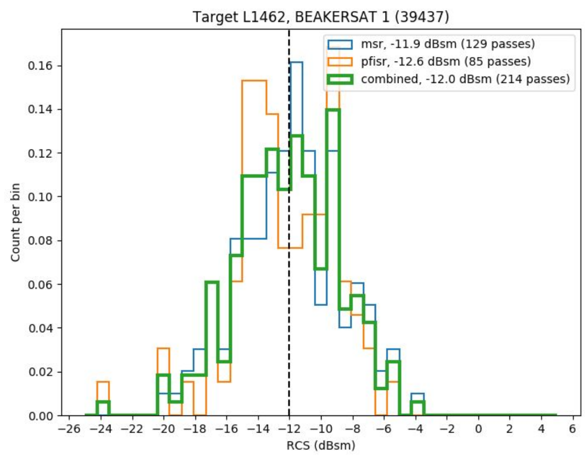
Satellite	Median RCS (dBsm)	Median RCS (m^2)	RCS Spread (m^2)
Dove-4 (39434)	-11.9 dBsm	0.06 m^2	0.05 m^2 (82%)
$50SAT (39436)	-21.7 dBsm	0.01 m^2	0.01 m^2 (87%)
BeakerSat-1 (39437)	-12.0 dBsm	0.06 m^2	0.07 m^2 (113%)
QubeScout-S1 (39443)	-16.4 dBsm	0.02 m^2	0.02 m^2 (84%)
SpaceBEE-1 (43142)	-8.9 dBsm	0.13 m^2	0.12 m^2(90%)
SpaceBEE-2 (43141)	-9.0 dBsm	0.13 m^2	0.11 m^2 (90%)
STEP Cube Lab (43138)	-10.7 dBsm	0.09 m^2	0.06 m^2 (71%)
AO-92 (43137)	-13.4 dBsm	0.05 m^2	0.06 m^2 (123%)
Aerocube-6A (40045)	-9.8 dBsm	0.10 m^2	0.08 m^2 (72%)
Aerocube-6B (40046)	-9.2 dBsm	0.12 m^2	0.12 m^2 (98%)
Rigidsphere-2 (5398)	-0.2 dBsm	0.96 m^2	0.44 m^2 (46%)
Stella (22824)	-5.2 dBsm	0.30 m^2	0.25 m^2 (83%)

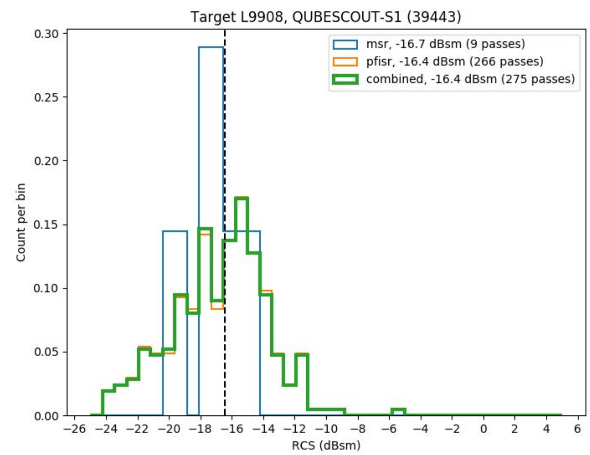
Table 4. Summary of RMS uncertainties for LeoLabs orbit determination. Data from 1/1/2019 through 11/25/2019 were included in this analysis. Values are reported at the epoch of the orbit determination.

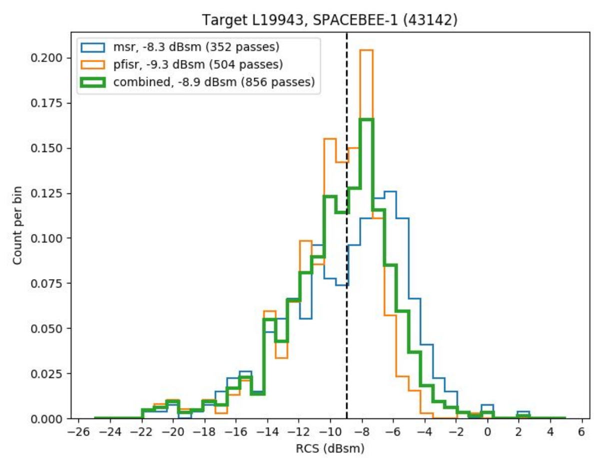
Satellite	Median RMS Error	%<1 km RMS	%<100 m RMS
Dove-4 (39434)	641.6 m	65.9%	5.1%
$50SAT (39436)	N/A	N/A	N/A
BeakerSat-1 (39437)	N/A	N/A	N/A
QubeScout-S1 (39443)	1766.2 m	34.0%	0.0%
SpaceBEE-1 (43142)	135.7 m	98.1%	38.6%
SpaceBEE-2 (43141)	133.2 m	99.3%	35.7%
STEP Cube Lab (43138)	145.7 m	94.6%	36.0%
AO-92 (43137)	191.0 m	81.0%	31.7%
Aerocube-6A (40045)	123.5 m	96.6%	35.6%
Aerocube-6B (40046)	117.7 m	98.2%	42.5%
Rigidsphere-2 (5398)	60.1 m	98.2%	78.8%
Stella (22824)	54.2 m	100.0%	81.8%

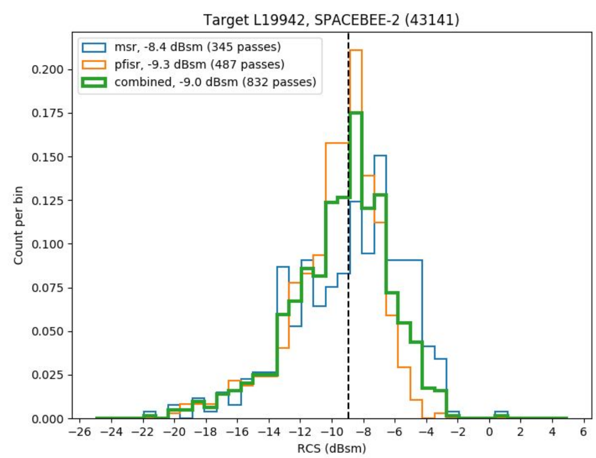

Target L7668, DOVE 4 (39434)
msr, -14.9 dBsm (105 passes)
pfisr, -11.3 dBsm (382 passes)
combined, -11.9 dBsm (487 passes)
Count per bin
RCS (dBsm)


Target L7703, 50 SAT (39436)
msr, -22.5 dBsm (11 passes)
pfisr, -21.4 dBsm (5 passes)
combined, -21.7 dBsm (16 passes)
Count per bin
RCS (dBsm)


Target L1462, BEAKERSAT 1 (39437)
msr, -11.9 dBsm (129 passes)
pfisr, -12.6 dBsm (85 passes)
combined, -12.0 dBsm (214 passes)
Count per bin
RCS (dBsm)


Target L9908, QUBESCOUT-S1 (39443)
msr, -16.7 dBsm (9 passes)
pfisr, -16.4 dBsm (266 passes)
combined, -16.4 dBsm (275 passes)
Count per bin
RCS (dBsm)


Target L19943, SPACEBEE-1 (43142)
msr, -8.3 dBsm (352 passes)
pfisr, -9.3 dBsm (504 passes)
combined, -8.9 dBsm (856 passes)
Count per bin
RCS (dBsm)


Target L19942, SPACEBEE-2 (43141)
msr, -8.4 dBsm (345 passes)
pfisr, -9.3 dBsm (487 passes)
combined, -9.0 dBsm (832 passes)
Count per bin
RCS (dBsm)

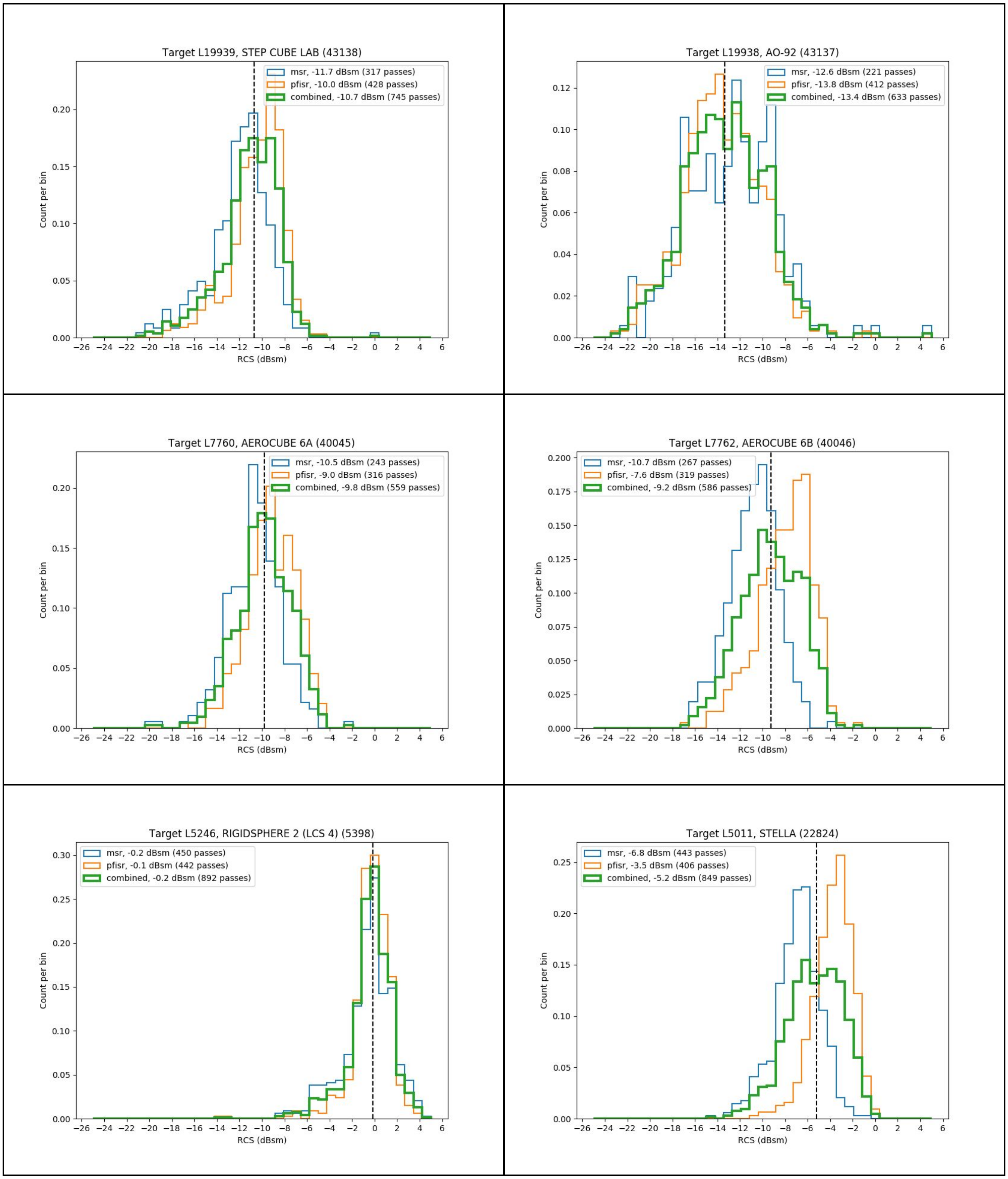


Figure 1. Histograms of RCS measurements for the 12 objects under study.