Micro-Meteoroid and Orbital Debris Radar from Goldstone Radar Observations

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ABSTRACT

Micro-meteoroid and orbital debris (MMOD) refers to millions of micrometeoroids and orbital debris orbiting the Earth, which can come from remaining parts of spacecraft from previous missions. These debris objects keep colliding and creating new pieces of debris, with very different sizes ranging from millimeters to meters. About 99.3% of the debris objects have a size < 1 cm. These debris objects, traveling at speeds of 10 km/s, can cause significant damage to spacecraft, satellites, and astronauts. Despite the historic use of shielding to protect vital spacecraft components, MMOD still present a potential hazard for future missions and operations involving humans in space. Goldstone's orbital debris radar (ODR) enhances the NASA orbital debris model with radar observation data, providing vital information on orbital debris detections: size, Doppler, range, and orbit inclination angle. These observations currently provide the only access to information about this size class (2 mm to 10 mm) of orbital debris. Goldstone's ODR experiments operate as a bistatic radar, with overlapping beams providing a wide distribution of ranges. From 2004 to early 2018, Goldstone's ODR has been collecting orbital debris data from altitudes covering 280 km to 3000 km. Since the decommissioning of the receive antenna in early 2018, Goldstone's range coverage is reduced to a 300 km window within a 600 km to 1000 km potential range coverage, depending on the pointing geometry and antenna station used. We are investigating alternative transmit receive configurations at Goldstone to recover our previous wide range coverage.

1 BACKGROUND

Micro-meteoroid and orbital debris (MMOD) refer to both naturally occurring meteoroids and debris objects within the Earth orbit that are generated by human activity. Orbital debris can come from remaining parts of spacecraft from previous missions. According to [1], known sources of orbital debris in low Earth orbit (LEO) include:

- spent intact satellites past end-of-life,
- mission-related debris (i.e., objects released in the course of spacecraft deployment and operations),
- fragments of intact satellite resulting from accidental or intentional explosions and collisions,
- radiator coolant droplets,
- ejected RORSAT nuclear cores,
- solid rocket motor exhaust products,
- ejecta from micro-particle impacts with intact satellite and fragment surfaces,
- and paint flakes (i.e., intact satellite and fragment surface degradation products).

Russia, United States, and China have exploded bombs in orbit, contributing lots of debris. Lincoln Labs twice orbited millions of X-band dipoles, which have been observed some 35 years later. The fragmentation or breakup process is responsible for over 60% of all cataloged objects in LEO today. Causes of fragmentation include space battery explosions, deliberate explosions or collisions, accidental on-orbit collisions, anomalous breakups, and breakups with unknown causes. An example of a 'non-catastrophic' collision is where the impactor is destroyed and the target spacecraft is cratered. While this can lead to an end-of-mission of an operational spacecraft, it does not result in a large number of lethal fragments being released into the environment. Collisions termed 'catastrophic' result in the complete fragmentation of impactor and target. Orbital debris objects can keep colliding and creating new pieces of debris. Orbital debris sizes range from millimeters to meters. About 99.3% of the debris objects have a size smaller than 1 cm. With orbit velocities of 10 km/s, these debris objects can cause significant damage to spacecraft, satellites, and astronauts. Despite the historic use of shielding to protect vital spacecraft components, MMOD still represent a potential hazard for future missions and operations involving humans in space. The small, high velocity particles are particularly hazardous to astronauts on Extra Vehicular Activity (EVA) from the International Space Station (ISS), the current Space X Cargo Dragon, and potential future SpaceX Crew and Cargo Dragon 2 and the Space Launch System/Orion Multi-Purpose Crew Vehicle (SLS/MPCV).

2 MOTIVATION

The NASA Orbital Debris Program Office (ODPO), funded by Office of Safety and Mission Assurance (OSMA) at NASA Headquarters, is the only organization in the United States that conducts a full range of research activities on orbital debris. To characterize the orbital debris populations, from LEO, the region below 2000 km altitude, to geosynchronous Earth orbit (GEO), the region near 35786 km, the ODPO relies on data from many different sources, including Goldstone's orbital debris radar (ODR). Based on measurement data from these sources, ODPO develops different models to support NASA missions and other space applications. The Orbital Debris Engineering Model (ORDEM) provides mathematical descriptions of the debris environment in terms of debris impact flux, debris size, mass, and other information needed for orbital debris impact risk assessments [2]. Figure 1 below shows altitude region and particle size that Goldstone's ODR data contributes [3]. Currently, Goldstone's ODR provide the only access to the lower millimeter size class orbital debris.

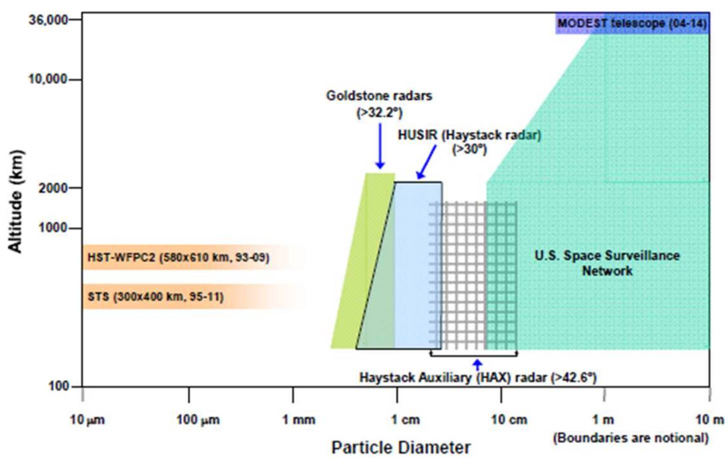


Fig. 1. Measurement data used by NASA ODPO to describe the orbital debris populations in the near-Earth space environment. Extracted from [3].

Unfortunately, there are gaps in available data for altitude, size, and inclination in the model, due to limitations of various data sources. Goldstone's ODR has been providing radar observation data to NASA's latest ORDEM 3.0 and future ORDEM 3.1, as shown in Fig. 2. ORDEM 3.0 has been released and is in use by several spacecraft and sensor programs to assist in vehicle safety and environmental studies.

Data Source	Region/Debris Size	Time Coverage (ORDEM 3.0)	Time Coverage (ORDEM 3.1)
JSpOC Catalog	LEO (>10 cm) GEO (>1 m)	Through 2008	Through 2015
HAX	LEO (>3 cm)	1999-2003	2007-2014
HUSIR (Haystack)	LEO (>5 mm)	1999-2003	2003, 2006-2010, 2014
Goldstone	LEO (>3 mm)	1996-1998, 2001, 2005-2006	2007-2014
STS Windows and Radiators	LEO (<1 mm)	1995-2011	1995-2011
MODEST	GEO (>30 cm)	2004-2006	2004-2009 2013-2014
HST WFPC-2 Radiator	LEO (<1 mm)	Not available	1993-2009

Fig. 2. Data sources for debris populations. Extracted from [3].

3 THEORY BEHIND MEASUREMENTS

Goldstone's ODR technique was developed by Goldstein [4]. The experiment protocol transmits alternating up and down chirp pulses. The repetition period is determined by the desired maximum detection range. For each receive period, our signal processing performs a convolution with replica transmitted chirp followed by threshold detection of the received signals. While the debris is in the beam overlap of the radar, the echo observables are the time delay for the up and down chirps, τ_{up} and τ_{down}, and their received echo power, P_R, at time, t. We require detections on both up and down chirps to qualify as a "hit" or detected orbital debris. This method takes advantage of the delay-Doppler coupling of chirps, where frequency offsets or Doppler can be seen as delay. With the observed delay from both up and down chirps in Eqs. 1 and 2, we can recover actual round trip time delay of the echo, τ, and Doppler, f, with Eqs. 3 and 4.

$$\tau_{up} = \tau - \frac{fT}{F} \quad (1), \qquad \tau_{down} = \tau + \frac{fT}{F} \quad (2)$$

$$\tau = \frac{\tau_{down}+\tau_{up}}{2} \quad (3), \qquad f = \frac{(\tau_{down}-\tau_{up})F}{2T} \quad (4)$$

where: T is the pulse duration of the transmitted chirp. F is the frequency excursion or chirp bandwidth. The chirp bandwidth is chosen to be large enough to accommodate the largest expected Doppler. It is important to note that more power is lost when the Doppler is closer to the maximum chirp bandwidth. Over the life of Goldstone's ODR, the chirp bandwidth has changed from 100 kHz to 300 kHz, allowing better detection under high Doppler.

Since the location and pointing geometry of the transmit and receive antennas is well known, the respective bistatic ranges, R_T and R_R can be easily determined, given the recovered round trip time delay, τ.

$$R_T = \frac{r^2-s^2}{2(-r\cos(\theta_{el})-s)} \quad (5), \qquad R_R = s - R_T \quad (6)$$

where: $s=c/\tau$ is the bistatic round trip range measurement in meters, c is the speed of light, r is the distance between antennas, and θ_{el} is the transmit antenna elevation angle.

Debris range or altitude, R, is defined as the shortest distance from the Earth's surface to the debris, which can be determined from the following:

$$R = \sqrt{R_T^2 + R_E^2 + 2R_E R_T \sin\theta_{el}} - R_E \quad (7)$$

where: $R_E=6378$ km is the Earth Radius, and $\theta_{el} = 90 - z$ is the transmit antenna elevation angle as a function of zenith angle of the transmit antenna, i.e. $z = 15$ deg.

The received signal power follows the standard bistatic radar equation:

$$P_R = \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 R^4 R_R^2 R_T^2} \quad (8)$$

where: P_T is the transmitter power, λ=3.5cm is the wavelength of transmitted signal at X-band, G_T is the gain of the transmitter antenna, G_R is the gain of the receiver antenna, σ is the apparent radar cross section of the debris. P_R can be easily calculated from the SNR estimate of each receive period. To estimate the particle size, we compare the radar cross section to that of an equivalent sphere of large dielectric constant. We use either the geometric cross section for larger debris, Eq. 9, or the Rayleigh cross section for smaller debris, Eq. 10, which models high-power radar echoes as Mie scattering.

$$\sigma = \frac{\pi}{4} d^2 \quad (9), \qquad \sigma = \frac{\pi^5 d^6}{\lambda^4} \quad (10)$$

As an example, for the geometric cross section case, combining the Eqs. 8 and 9 above gives us the debris particle size in diameter, d:

$$d = 4\sqrt{\frac{P_R (4\pi)^2 R_R^2 R_T^2}{P_T G_T G_R \lambda^2}} \quad (11)$$

In order to measure orbital inclination, Goldstone's ODR is collected by "staring" at 75 degree elevation, 90 degree azimuth angles, referred to as "75 deg. East" data [5]. Using this beam position, prograde and retrograde orbits have very different range rates. As elevation angle decreases, Doppler rate increases but so does inclination ambiguity and the slant range to an altitude. The "75 deg. East" data represents a compromise between Doppler resolution, inclination ambiguity, and the slant range for detection of an object. Orbital inclination (i) can be calculated from both the Doppler frequency and the range, assuming the orbit is circular.

$$\cos(i) = \cos(\theta)\cos(\alpha) \quad (12)$$

where θ is the latitude of the transmitting antenna (i.e., Goldstone radar is at 35.24 degrees) and α is defined below:

$$\cos(\alpha) = \frac{\frac{-f\lambda}{2\sin(z)} + \upsilon_e}{\upsilon_d}, \qquad \upsilon_d = \sqrt{\frac{GM_E}{r_d}}, \qquad r_d = R\sin(z) + R_E, \qquad \upsilon_e = 2\pi R_E \cos(\theta)\frac{K_1}{D_S}$$

where: υ_d is the relative velocity of debris, G is Newton's gravitational constant and M_E is the mass of the Earth, so GM_E = 398600 km^3/s^2. r_d is the radius of the debris orbit, υ_e is the eastward velocity of DSS-14, K_1 = 1.00274 cycle/day the tidal frequency due to the moon and D_S = 86400 s/day.

The radial velocity or line of sight velocity can be extracted from the measured Doppler, *f*. This will not necessarily be the same as the relative velocity of debris defined above.

4 DISCUSSION OF MEASUREMENTS

Goldstone ODR observations began with a frequency of every two weeks to as often as four times a month. A typical observation collects 4 to 10 hours of data. The measurements of orbital debris require a bistatic radar setup involving two antennas. Ideally the transmit antenna and receive antenna should be located close enough so that the beams create a large area of intersection providing a wide distribution of ranges in LEO. From the time Goldstone's ODR was developed till early 2018, the transmit antenna was Deep Space Station (DSS)-14, a 70-meter dish with a high power 450 kW transmitter at an FCC radar band (8560 MHz) and the receive antenna was DSS-15, a 34-meter dish located about 497 meters away capable of receiving this band. This antenna location and pointing geometry provided a beam intersection corresponding to a range coverage of 280 km to 3000 km. The lower crossing point and upper crossing point in the beam overlap shown in Fig. 3 determine the full range coverage of that given setup.

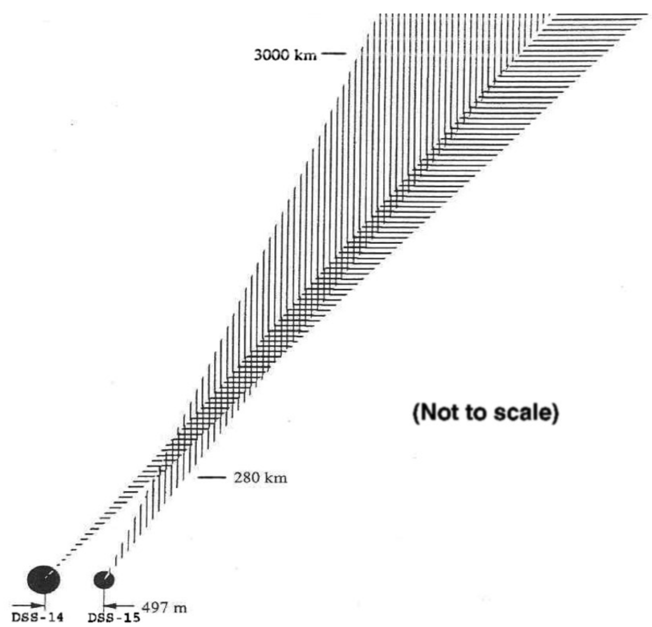


Fig. 3. Location and beam intersection geometry of transmitting and receiving antennas

Any detected debris or object within the 2 mm to 10 mm size scale passing through the beam overlap during the observation time can be characterized and added to the NASA orbital debris model. Figure 4 describes different aspects of the measurements obtained from one of many DSS-14 to DSS-15 observations as a sample of what Goldstone's ODR provides.

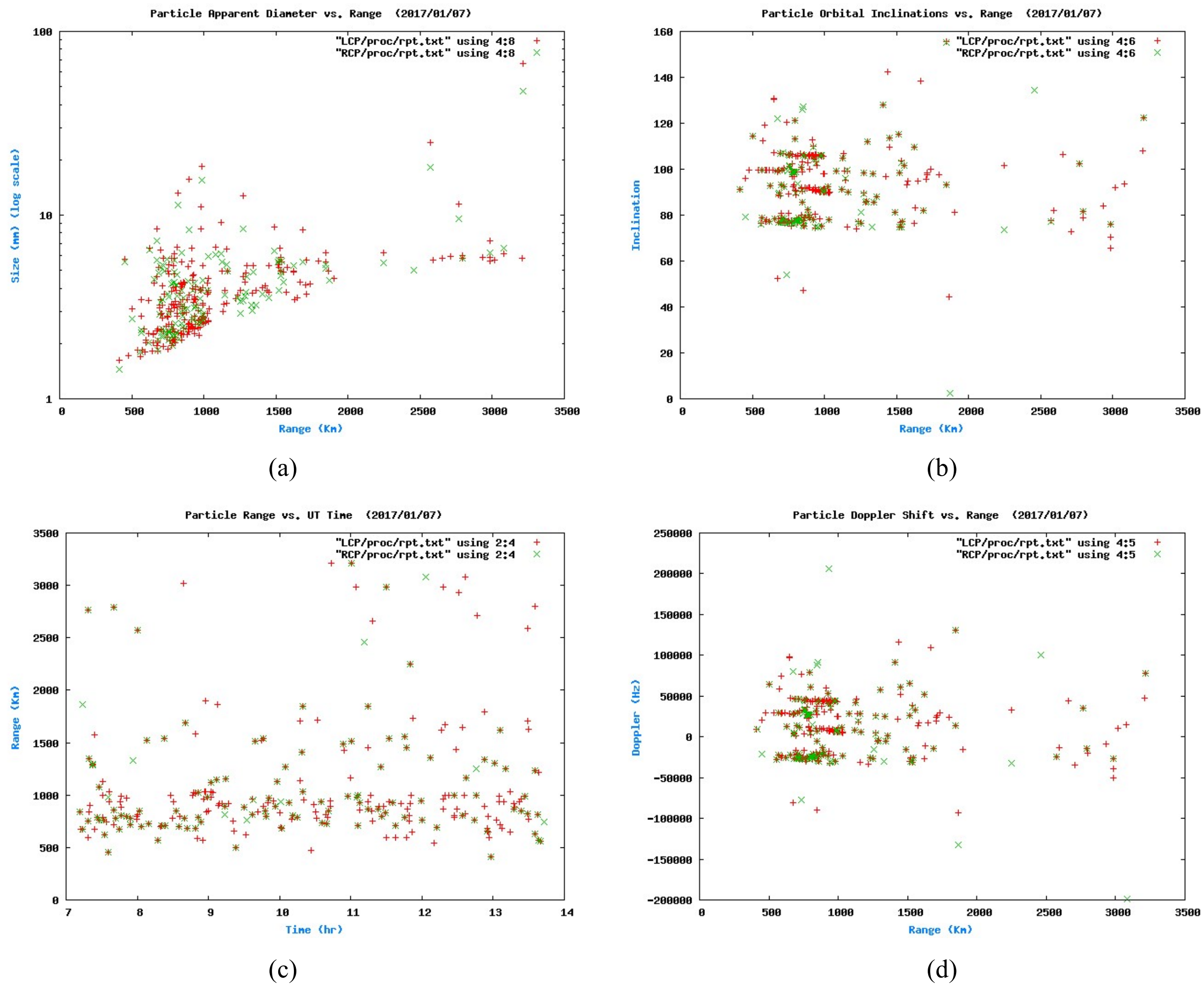


Fig. 4. Results from DSS-14 to DSS-15: (a) measured orbital debris size vs range, (b) orbital debris inclination vs range, (c) orbital debris range vs time, and (d) orbital debris Doppler vs range.

Figure 4-a shows the size of the orbital debris measured as a function of altitude or range in km. Overall the population of measured orbital debris seems to concentrate between 500 km and 1000 km, with sizes between 2 mm and 7 mm. Figure 4-b shows the orbit inclination of the measured debris as a function of the range, with most of the debris objects showing inclination values between 78 and 120 degrees. Figure 4-c shows the range distribution during the 7-hour duration observation which extends from 280 km to 3000 km. Figure 4-d shows the Doppler of the measured orbital debris as a function of range, with the majority of debris objects within -25 kHz and 70 kHz. A typical observation with this setup collects about 45-50 debris detections or hits per hour.

Goldstone's ODR transmits right-hand circular polarization (RCP). Initially only the opposite circular (OC), i.e. left-hand circular polarization (LCP), was received. But currently both polarizations are used, since information on the composition of the orbital debris can be determined based on the echo polarization received. Circularly polarized signal is reversed upon reflecting from a smooth dielectric interfaces leading to dominance of echoes by the OC polarization. Same circular (SC) or RCP echo power can arise from multiple scattering, from single backscattering from interfaces with subsurface reflections, wavelength-scale facets, or structure with radii of curvature near the wavelength [6]. With the size scale of orbital debris observed, wavelength scale features are irrelevant. For orbital debris that are rotating flat plates, OC echoes will dominate. Subsurface reflections due to composition of the debris objects would produce SC echoes.

In early 2018, the Deep Space Network (DSN), which runs Goldstone, decommissioned DSS-15, one of the DSN's older 34-meter High Efficiency (HEF) antennas, in order to reduce cost of maintenance. While Goldstone's ODR can still transmit with DSS-14, the closest receive antenna is now located at Apollo station, the location of the newer Beam Wave Guide (BWG) 34-meter antennas. DSS-25 or DSS-26 at approximately 9.8km away have been modified to accommodate receiving the radar band. The greater distance between transmit and receive antennas means the beam intersection will be much smaller, significantly reducing the range coverage of Goldstone's ODR in this configuration. The altitudes of intersections range from an approximate 300 km window within 600 km to 1000 km depending on the pointing angles. A map of DSN's Goldstone Deep Space Communications Complex in Fig. 5 below shows the location of various antennas.

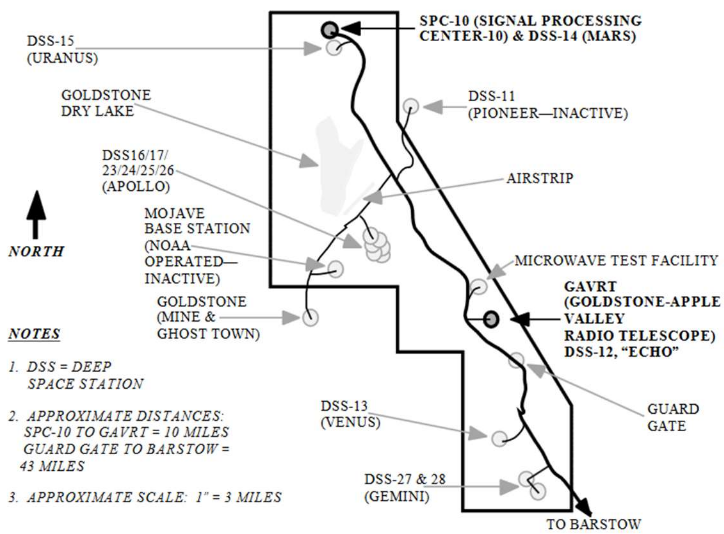
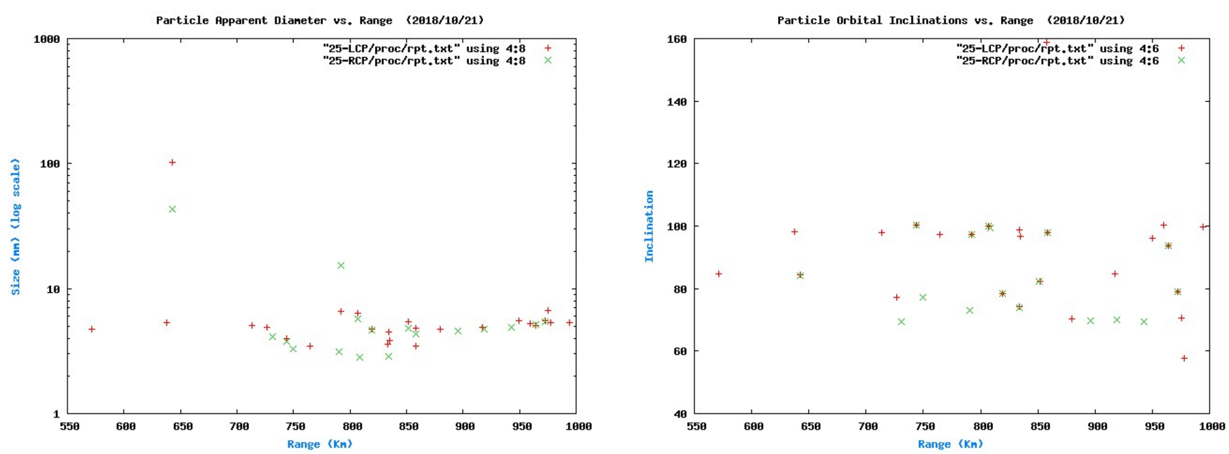
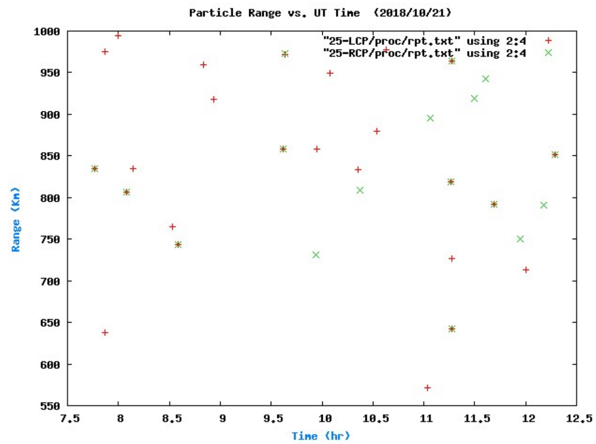


Fig. 5. Map of Goldstone Deep Space Communications Complex [7]

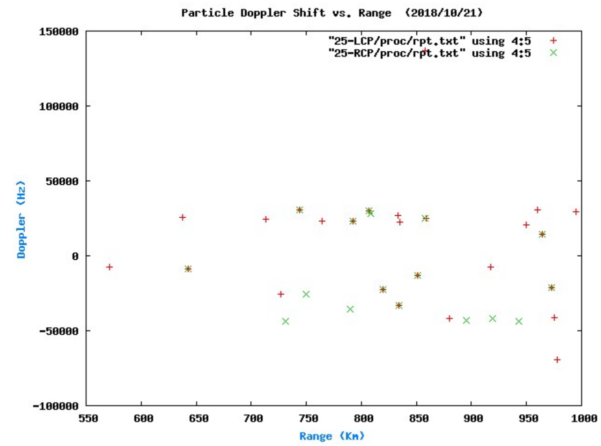
An experiment was conducted to see the observed orbital debris detection impact due to the change in antenna configuration. Unfortunately, DSS-14 lost full power transmit capability when one of its klystrons failed.



(a) (b)



(c)

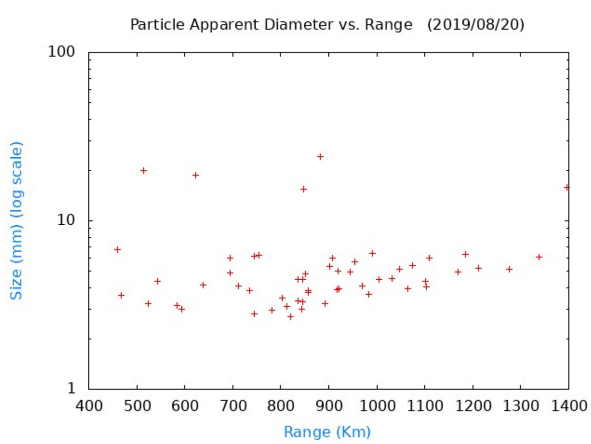


(d)

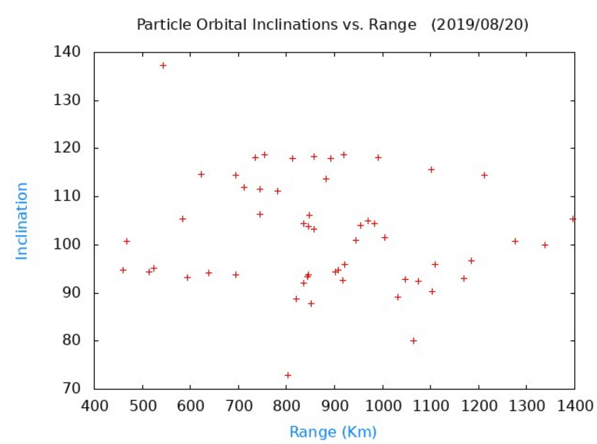
Fig. 6. Results from DSS-14 to DSS-25: (a) measured orbital debris size vs range, (b) orbital debris inclination vs range, (c) orbital debris range vs time, and (d) orbital debris Doppler vs range.

Figure 6 shows the same measurements to those described in Fig. 4 using DSS-25 as receive antenna instead of DSS-15. The reduction in debris detections can be seen in Fig. 6-c. This setup reduced the range coverage to 750 km to 860 km. However, this region of altitudes was requested specifically by NASA Johnson Space Center (JSC) for orbital debris data. This configuration produce about 8-10 hits per hour. The significant reduction in hits or debris detections was a result of the reduced range coverage as well as the reduced transmit power from DSS-14. The loss of one klystron reduced DSS-14 transmit power to about 100 kW. The experiment will have to be repeated again when DSS-14 is back at full power in the middle of 2020. But ultimately, the range coverage of this bistatic setup is not sufficient. Using DSS-14 transmit to DSS-25/26 receive, Goldstone's ODR will not be able provide important orbital debris data near important altitude regions like the International Space Station (ISS) or Hubble Space telescope.

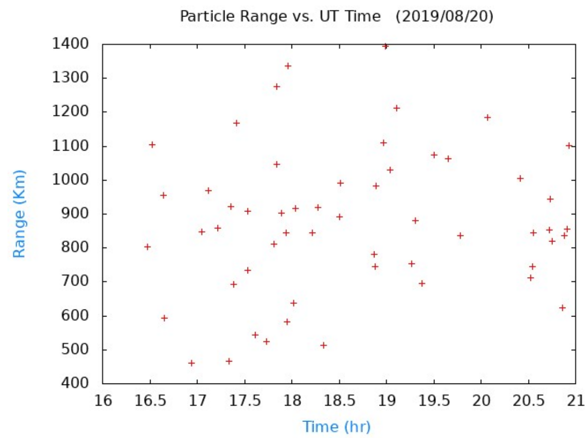
In an attempt to achieve better range coverage, some modifications were made to accommodate using a non-standard operating DSN antenna setup with DSS-13 transmitting to DSS-28 receiving. DSS-13 and DSS-28 are about 1 km apart. This configuration provides an expected range coverage from 520 km to 1760 km. While this setup has better range coverage, DSS-13 transmitter can only provide 80 kW, which is significantly less than DSS-14's 450 kW. This will likely result in fewer debris detections or counts. DSS-13 can only transmit at the standard DSN spacecraft uplink band, 7190 MHz. The standard DSN spacecraft downlink band is at a different band. This limits the receive station to DSS-28, which was specially modified for this purpose. Figure 7 shows the results for the experiment in this new configuration. Also notice only one polarization (LCP) can be received with DSS-28.

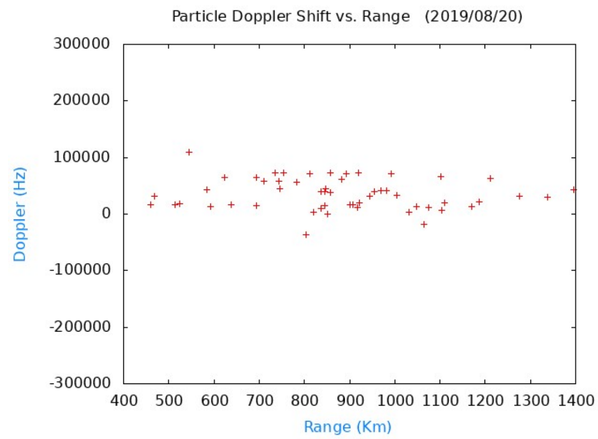


(a)



(b)





(c) (d)

Fig. 7. Results from DSS-13 to DSS-28: (a) measured orbital debris size vs range, (b) orbital debris inclination vs range, (c) orbital debris range vs time, and (d) orbital debris Doppler vs range.

As it can be seen in Fig. 7, the range of the observed debris extends from 400 km to 1400 km, i.e. a window of 1000 km. DSS-13 to DSS-28 produced 12-15 hits per hour. This is an improvement from the DSS-14/DSS-25 setup. However, this setup has a few drawbacks. Currently, DSS-28 can only receive one polarization (LCP). This can be easily fixed in the future by installing a second fiber channel to bring the SC channel to the backend receiver. As mentioned earlier, DSS-13 has much lower transmit power than DSS-14, which will impact the number of detections on lower SNR debris objects.

Note that it is possible to get detections or hits outside the beam overlap range bounds. In the latter observation setups, the chirp repetition period is sized larger than the range bounds. Actually, in all antenna setups, the same waveform was used, to prevent setup errors. So, the repetition period is really only configured for the original ODR setup. The hits outside the range bounds are likely multipath detections and should be classified as false detections and discarded.

5 CONCLUSION

Prior to the decommissioning of DSS-15, Goldstone's ODR has provided valuable exclusive millimeter scale debris data to NASA ODPO. Since its decommissioning we have yet to recover such capability fully. Orbital debris detection has been reduced from 45-50 hits/hour to 8-10 hits/hour. In addition, the range coverage has been reduced from (280 km to 3000 km) to (700 km to 860 km). However, we are still in the process of investigating different antennas configurations to allow Goldstone's ODR to continue to provide exclusive orbital debris data as described in Fig. 1. We also expect to return to full power of 450kW at DSS-14 in the near future. The DSS-14 transmit to DSS-25/26 receive setup will have to be repeated. Future work will involve exploring possibility of using DSS-25 transmit and DSS-26 receive for smaller baseline, resulting in significantly better range coverage. Due to the difference between the DSN uplink and downlink bands, extensive modifications will be needed to accommodate this ODR configuration. This is an important consideration since not all antennas will be available for ODR without extensive modifications. DSS-25 will not have the transmit power of DSS-14, but the altitude range coverage is important in recovering orbital debris data in a key exclusive region.

6 ACKNOWLEDGEMENTS

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