A Survey of Radars Capable of Providing Small Debris Measurements for Orbit Prediction

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Introduction

- Estimates have more than 20,000 debris objects with diameters larger than 10 cm (and 600,000 with diameter larger than 1 cm) orbiting the earth (Ref: Air&Space April 6,2011)
  - Researchers are tracking only 22,000 chunks of debris
- Debris larger than 1 cm can be lethal to current spacecraft
- The ODERACS Radar Experiments were conducted to calibrate and develop strategies for small debris detection and track[1]
  - Haystack, ESA FGAN TIRA[2], Russian SSN (Don-2N)[3]
  - USSN (FPS-85)
- Historically, radar measurements of debris has concentrated on measuring the density of objects < 10 cm
  - US (Haystack and HAX), ESA (FGAN TIRA)
- Measurements are used to Model Debris Density and Flux to establish debris collision risk to spacecraft
- A requirement exists to track and catalog small debris

Use of Radar Sensors to Model Debris

- NASA/ESA have sponsored measurement and modeling efforts to characterize the LEO debris environment[4]
  - The NASA Size Estimation Model (SEM) derives size from RCS data samples
  - NASA's ORDEM Model and ESA's MASTER Model are current debris models
- The US Space Surveillance Network (UHF and VHF radars) catalog builds the 1-m and 10-cm populations
  - Haystack (X-band) and HAX (Ku-band) radar data build the 1-cm population
- FGAN TIRA L-Band radar data used to validate 2-cm population

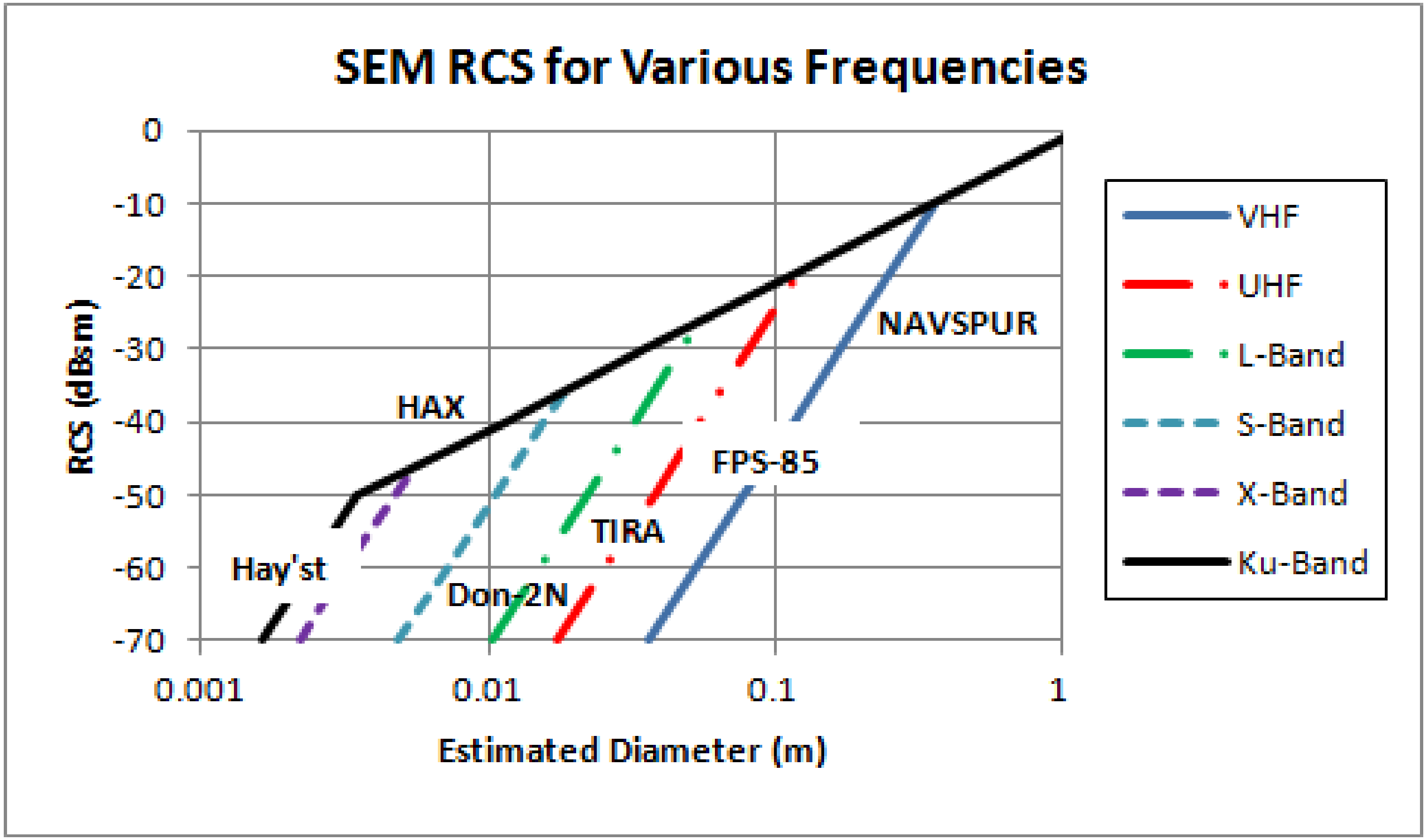
The radars do not catalog the population

Current Capability Issues

- To assess the capability of current radars to generate tracks/element sets on space debris 1 to 10 cm in diameter the issues to be addressed include:
  - The current sensitivity (detectable RCS vs range)
  - The track capability (track time, measurements errors)
    - Improvements to achieve precision small debris track data with changes in current operating modes (FPS-85 high elevation "Debris Fence"[5])
- Identify multiple radar tracking network for track data exchange and experimentation

Multi Radar Network Decreases Time Between Tracks, Aids Reacquisition and Increases Cataloging Capability[6,7]

Radar Frequency Sensitivity



Frequencies above S-band required to detect debris down to 1 cm

World Radar Radars Able to Detect and Track Small Space Debris

- Initial 1993-1995 ODERACS experiments with calibration spheres (5, 10 and 15 cm) identified a number of radar systems that can detect small debris
  - Haystack, TIRA, Don-2N (Pill Box)
- Haystack Dish Radar was able to track the 10 and 15 cm spheres using cued search routines
- TIRA L-Band Dish Radar ODERACS measurements were statistical analyzed and compare with NASA RCS results
- Don-2N C-Band Phased Array Radar was able to detect and construct a trajectory on the 5 cm sphere using cued search routines
- FPS-85 detected and tracked <10 cm debris in special debris fence

Future Debris Radar Development

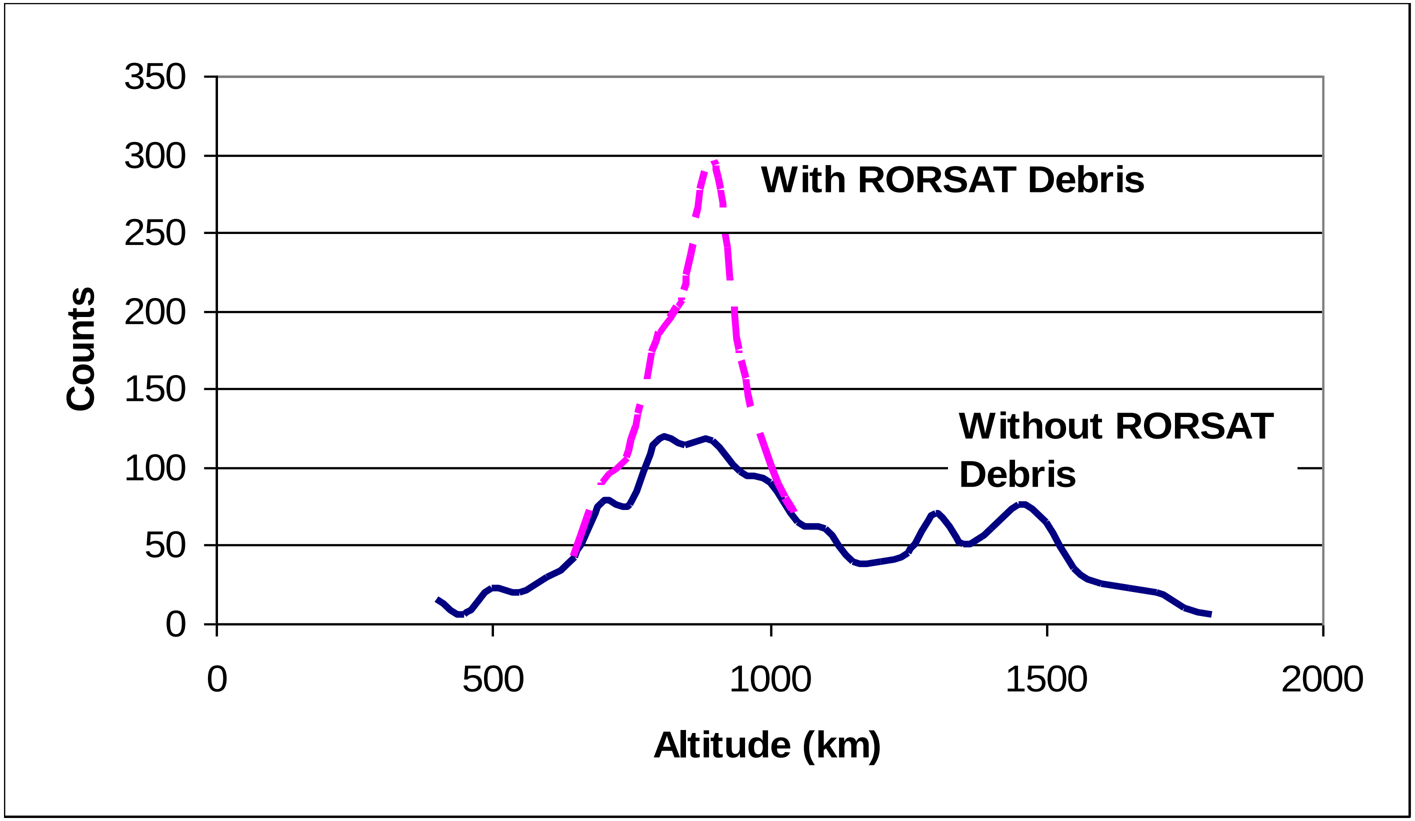
- The US is developing a Space Fence radars to provide timely assessment of space objects, events and debris
  - 2-3 geographically dispersed ground based S-Band phased array
    - Vertical Fan Beam Design, expected to detect 100,000 objects
  - First radar to be located on Kwajalein Island
    - Construction scheduled to begin in 2013 with Operational Capability planned for 2017
- ESA investing in testing space debris radar technology[8]
  - First monostatic test radar installed in Spain in 2012
  - Second Bistatic test radar to be installed in France, worked began in September 2012

Haystack/HAX Detections[9]

- HAX (12.2m parabolic reflector) became operational in 1994 and has been used to observe the LEO debris environment
  - Although its sensitivity is lower than Haystack it has a wider field of view (1.7 times that of Haystack)
  - The HAX observation mode is currently 75 deg east
  - The average debris diameter detected is from 2 cm to several meters (based on the NASA Size Estimation Model, SEM).
- Haystack (36.6m parabolic reflector) generally detects debris from less than 1 cm to several meters
- The Haystack/HAX debris detections are of limited quality to determine the particle's eccentricity accurately.
  - These measurements represent statistical samplings of the population, and are thus subject to sampling error.

Haystack FY 2003 Collection

75º East



RORSAT NaK Debris is generally < 2cm

FPS-85 Detections[10]

- The FPS-85 Phased Array Space Surveillance Radar, operational in 1969, is the only US phased array radar dedicated to space surveillance
  - Collects 16 million satellite observations per year
  - Can detect, track and identify up to 200 space objects simultaneously
  - Only phased array radar capable of tracking deep space objects (can track a basketball size object at 22,000nm)
    - The boresight is at 45^{o}, the nominal low elevation surveillance fence is at 20^{o} elevation
- The FPS-85 has upgraded software (1999) to erect a high elevation "debris" fence[5]
  - Developmental testing of a fence at 35^{o} enables detection of objects greater than -35dBsm

FGAN TIRA Detections[11]

- The FGAN Tracking and Imaging Radar (TIRA) is the high performance European facility able to track and image space objects
  - The 34-m parabolic antenna operates with a narrow-band mono-pulse L-band tracking radar, and a high resolution Ku-band imaging radar.
  - The FGAN radar is sensitive enough to detect 2 cm sized objects at 1000 km.
- The TIRA L-Band radar operated in beam park mode in 1994 for 24 hours in 1994 collecting debris detections

Don-2N Detections[12]

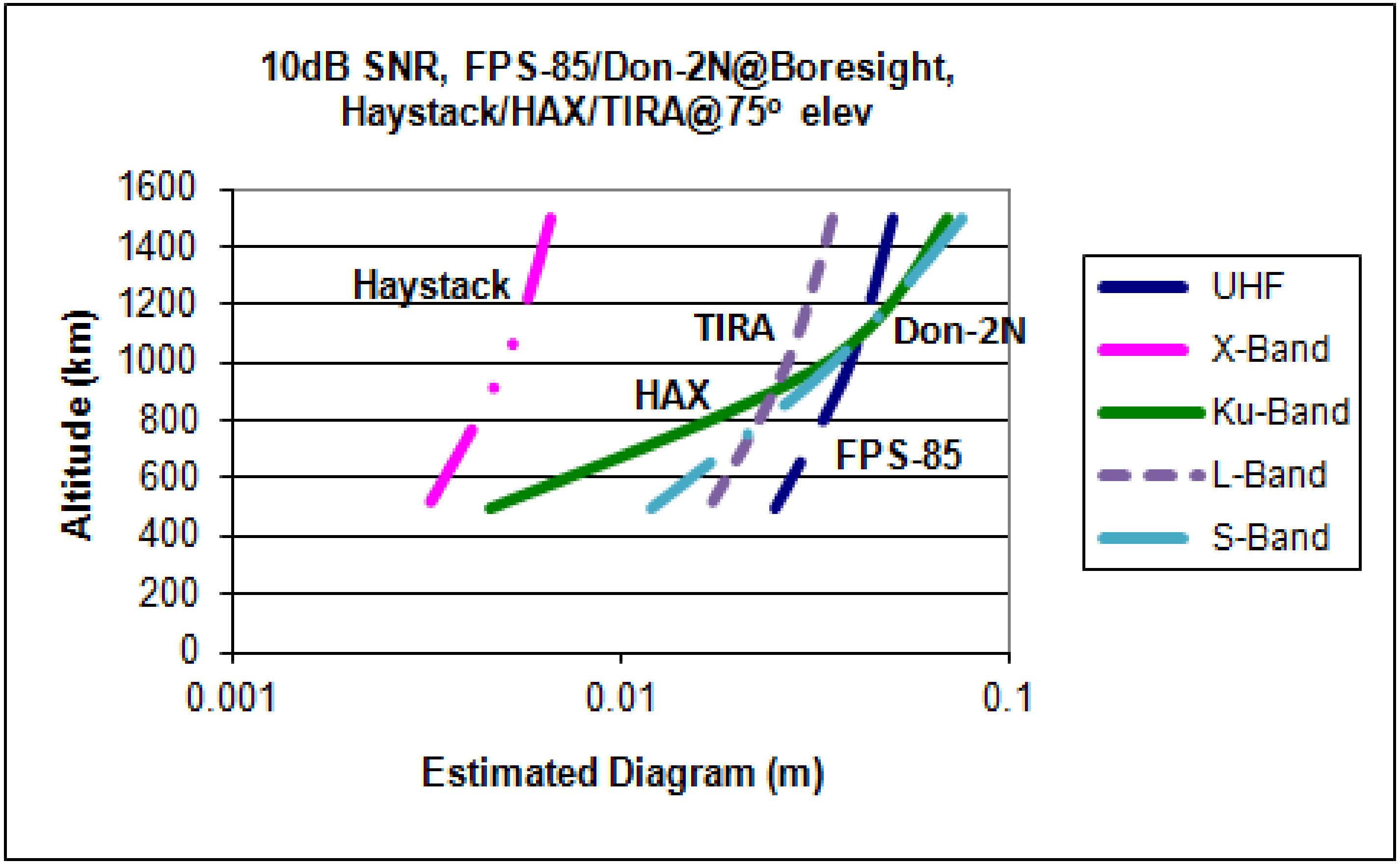
- The Don-2N (16 meter diameter) phased-array radar reached full operational capability around 1989 and was integrated into the early warning network
  - Built as a missile defense battle-management radar
  - Four face radar for 360^{o} azimuth coverage
- The Don-2N participated in the "ODERACS" experiment in 1994[13]
  - The radar was able to detect and track the smallest 5 cm sphere
  - In 2007 a launch of an ABM interceptor was made to test new computational software upgrades to the system

Radar Parameters
(Radars in debris collection modes)

Radar Parameter	FPS-85[5,14,15] (Trans/Rec)	Haystack[9]	HAX[9]	TIRA[11] (L/Ku)	Don-2N[16]
Peak Power (kW)	32000	250	50	2000/13	25000
Frequency (GHz)	0.442	10	16.7	1.3/16.7	4
Beamwidth (deg)	1.3/0.7	0.058	0.10	0.5/0.039	0.27
Antenna Gain (dB)	43/48	64	67	51/73	57
Available LFM BW (GHz)	0.001	1	2	0.06/0.8	0.0033
Pulse width (msec)	0.25	1.64	1.64	1/0.26	0.0625
Single Pulse SNR on 0dBsm @ 10^3 km (dB)	64	59.2	40.6	51.2/27	45

Predicted Radar Performance[17]

(Single Pulse)



Radar Measurement Errors[18]

- The radar range measurement error, σ_r is generally defined as the root-sum-square of three error components[10]

$$\sigma_r = (\sigma_{rn}^2 + \sigma_{rf}^2 + \sigma_{rb}^2)^{1/2}$$

  - where $\sigma_{rn} = \Delta R/(2(S/N))^{1/2}$, ΔR is the radar range resolution approximately equal to the reciprocal of the radar bandwidth; σ_{rf} is the range fixed random error due to random noise in the receiver and is equivalent to a 20dB S/N error; and σ_{rb} is the range bias error, since these are the same over a series of track pulses they do not affect track results
- The radar bandwidth, pulse width, will establish single pulse range error limits

Radar Measurement Errors

	Noise Error at Max Sensitivity (SNR 10dB)			Fixed Error at SNR 20dB &1/50 Beamwidth		
	Range Error (m)	Range Rate Error[a] (m/s)	Angle Error (deg)	Range Error (m)	Range Rate Error[a] (m/s)	Angle Error (deg)
FPS 85 LFM (max)	33.0	-	0.18	11.0	-	0.026
Haystack LFM (max)	0.03	2.0	0.008	0.01	0.65	0.0012
HAX LFM (max)	0.02	1.3	0.014	0.006	0.41	0.002
TIRA (L-Band) Max BW	0.5	-	0.07	0.167	-	0.0014
Ron-2N Max BW	10.0	-	0.037	3.33	-	0.0054

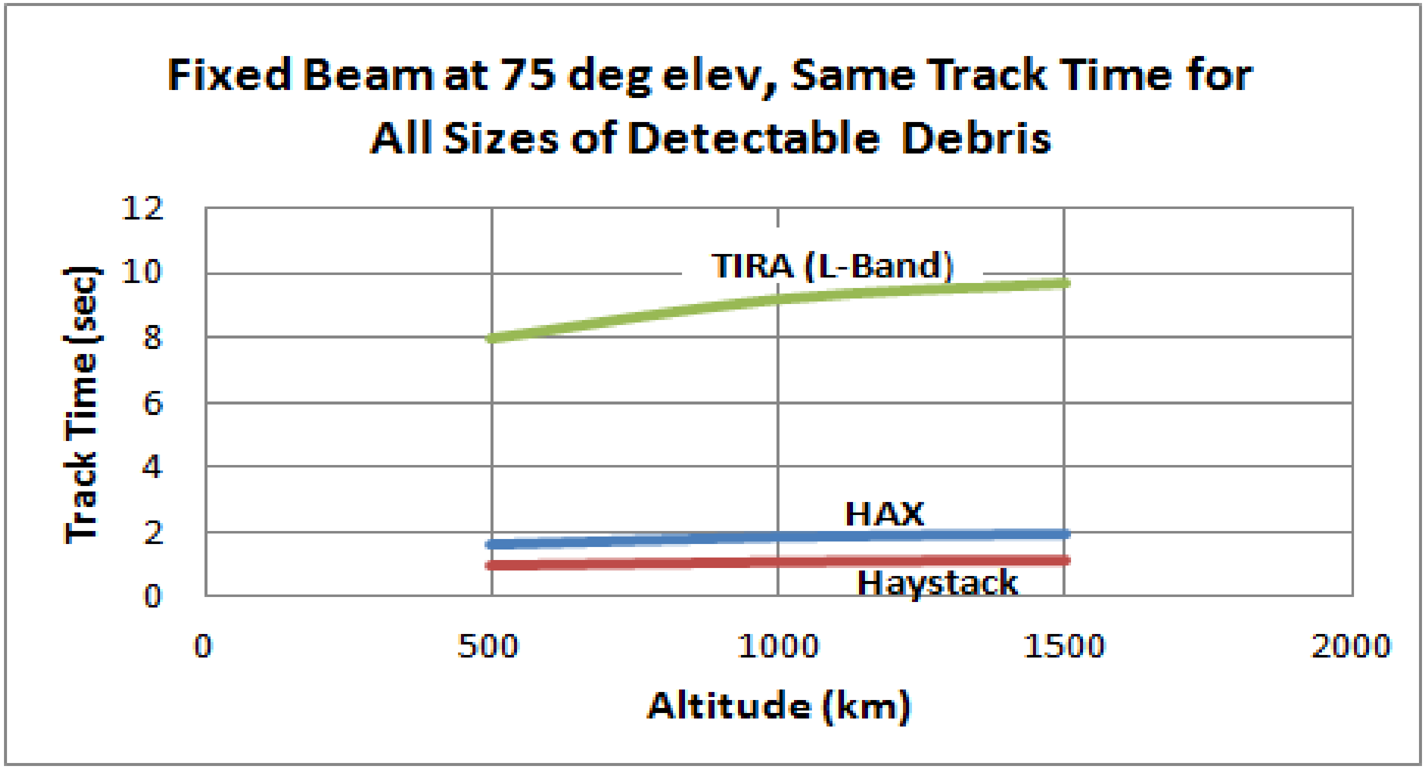
[a]Assumes doppler measurement

Orbital Element Errors[19]

- Of the six orbital elements the following three are the most accurately determined by radar measurements;
  - *i*, the inclination of the orbital plane (deg)
  - Ω, the longitude of the ascending node (deg)
  - *T*, the orbital revolution period (min)
- The approximate relationships for the errors associated with these elements are given as;
  - $\varsigma_{\Omega} = 0.0123(R\sigma_\theta \pi/180) + 9.6(R\sigma_r/t_r^2)\sin i$ (deg)
  - $\varsigma_i = 0.0123(R\sigma_\theta \pi/180) + 9.6(R\sigma_r/t_r^2)$ (deg)
  - $\varsigma_T = 48(R\sigma_r/t_r^2) + 0.025(R\sigma_\theta \pi/180)$ (min)

  where R (km) is the radar range to the target, t_r (sec) is the total track time, σ_r (km) is the sigma range error, and σ_θ (deg) is the sigma angular error, the numerical coefficients have appropriate units to make the equations consistent

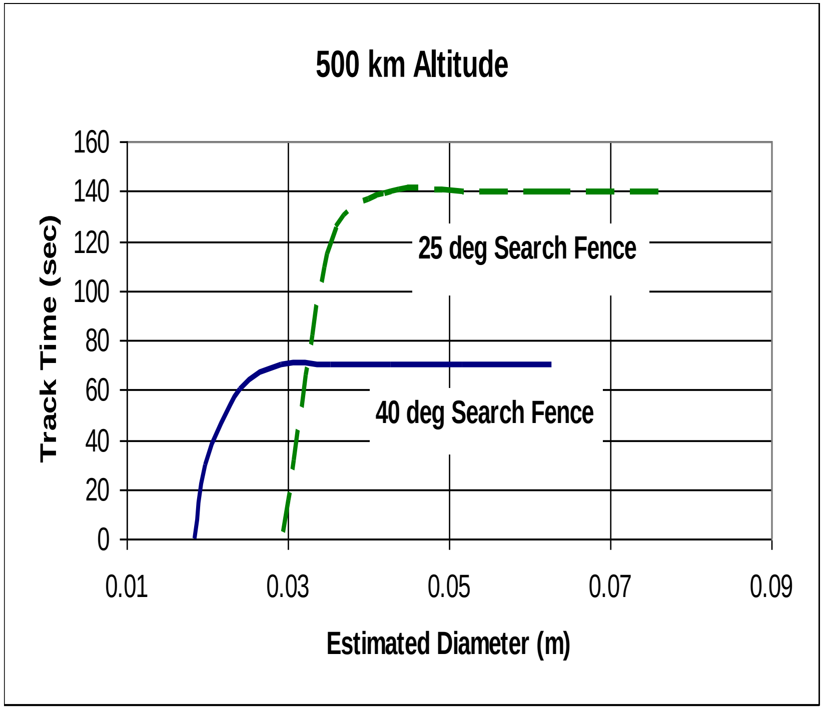
Available Fixed Beam Radar Track Time

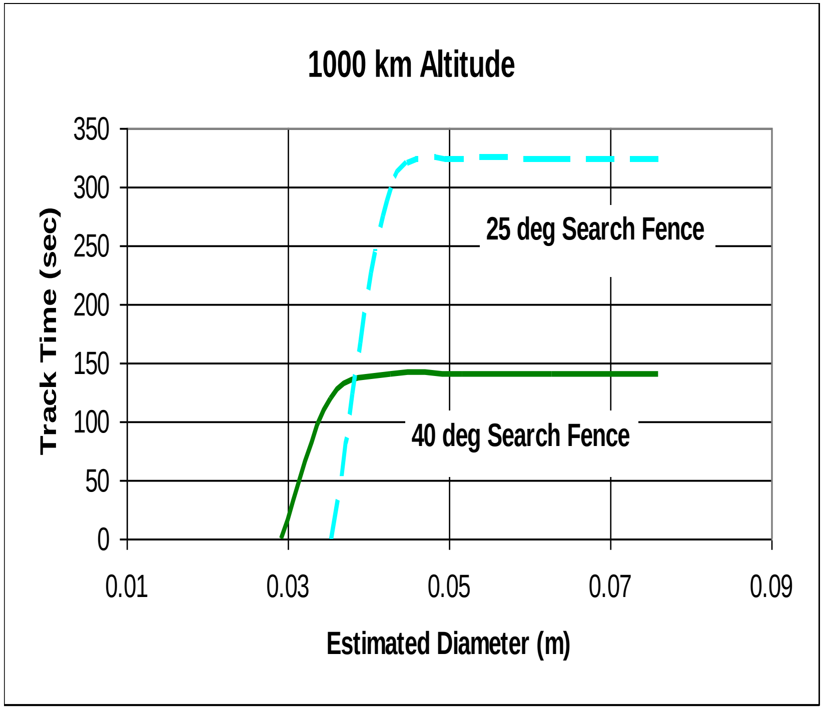


The Fixed Beam Radars track time is based on beamwidth,

Available FPS-85 Track Time

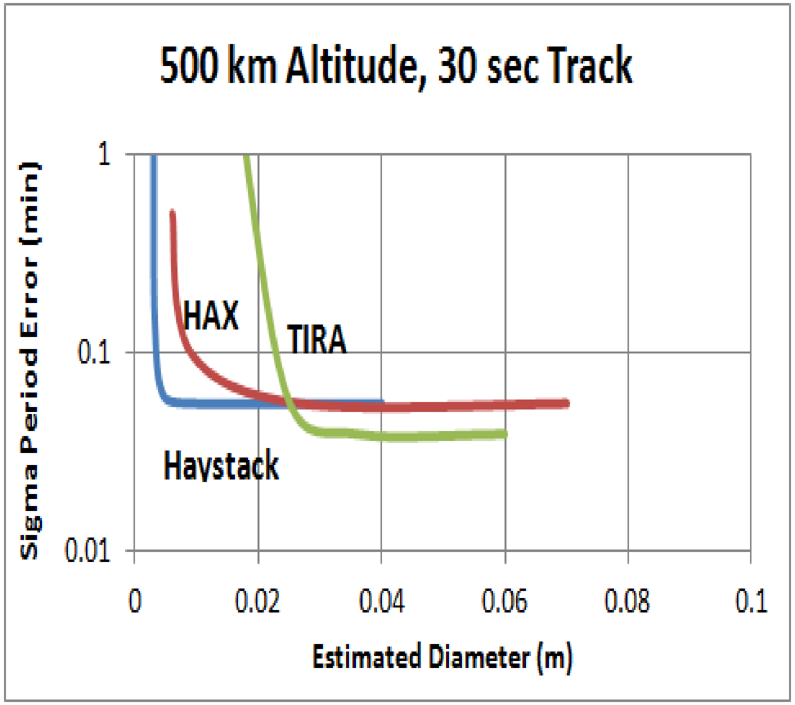
70deg Incl, Ascending Passes thru Boresight

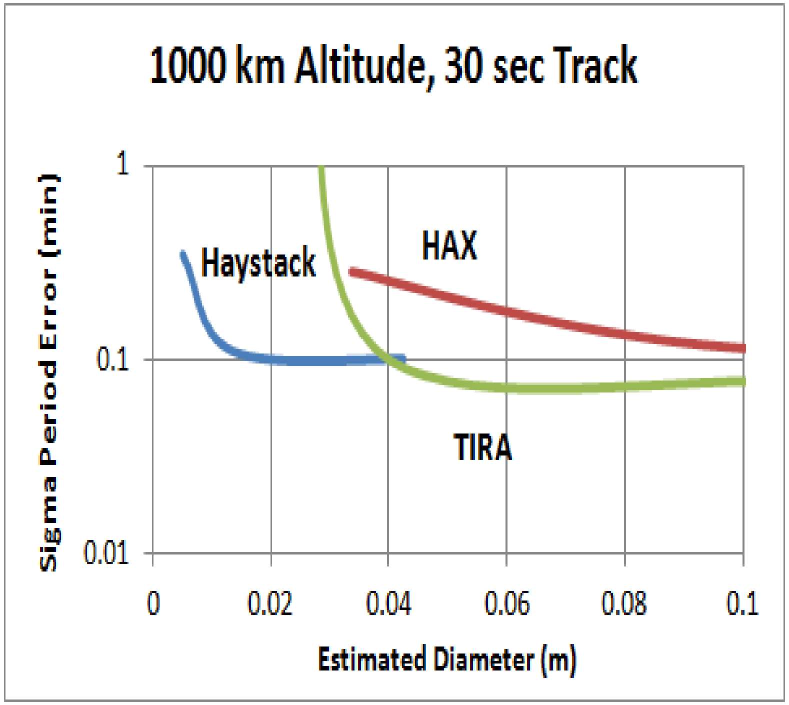




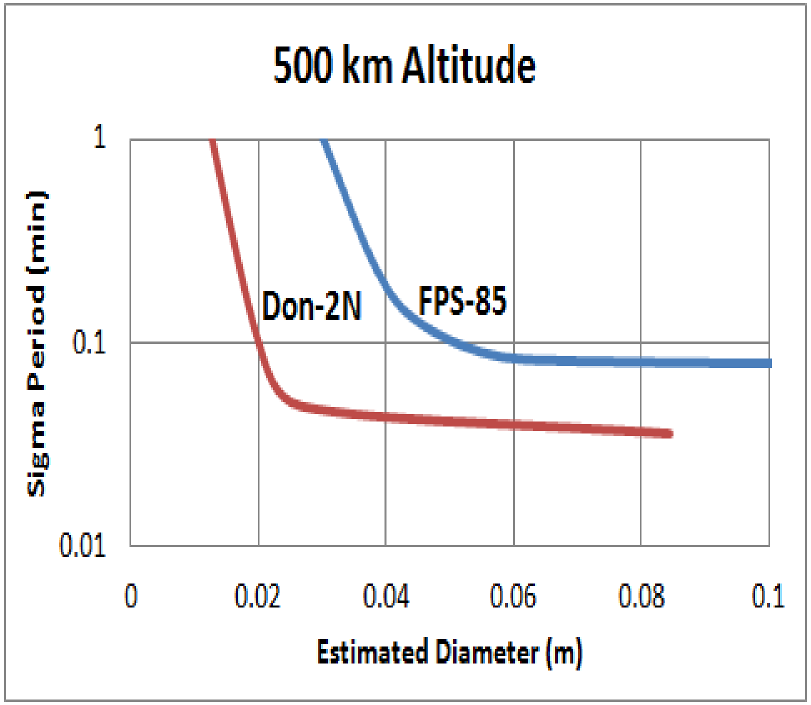
Array Radar track time is based on sensitivity and FOV

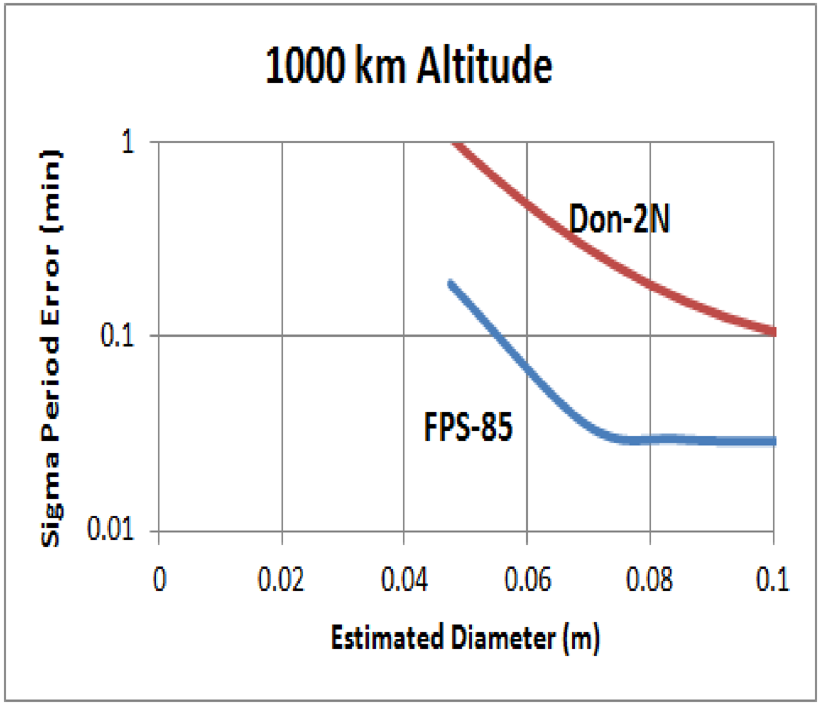
Cued Dish Antenna Period Error
(Single Pulse)





Phased Array Period Error
(Single Pulse)





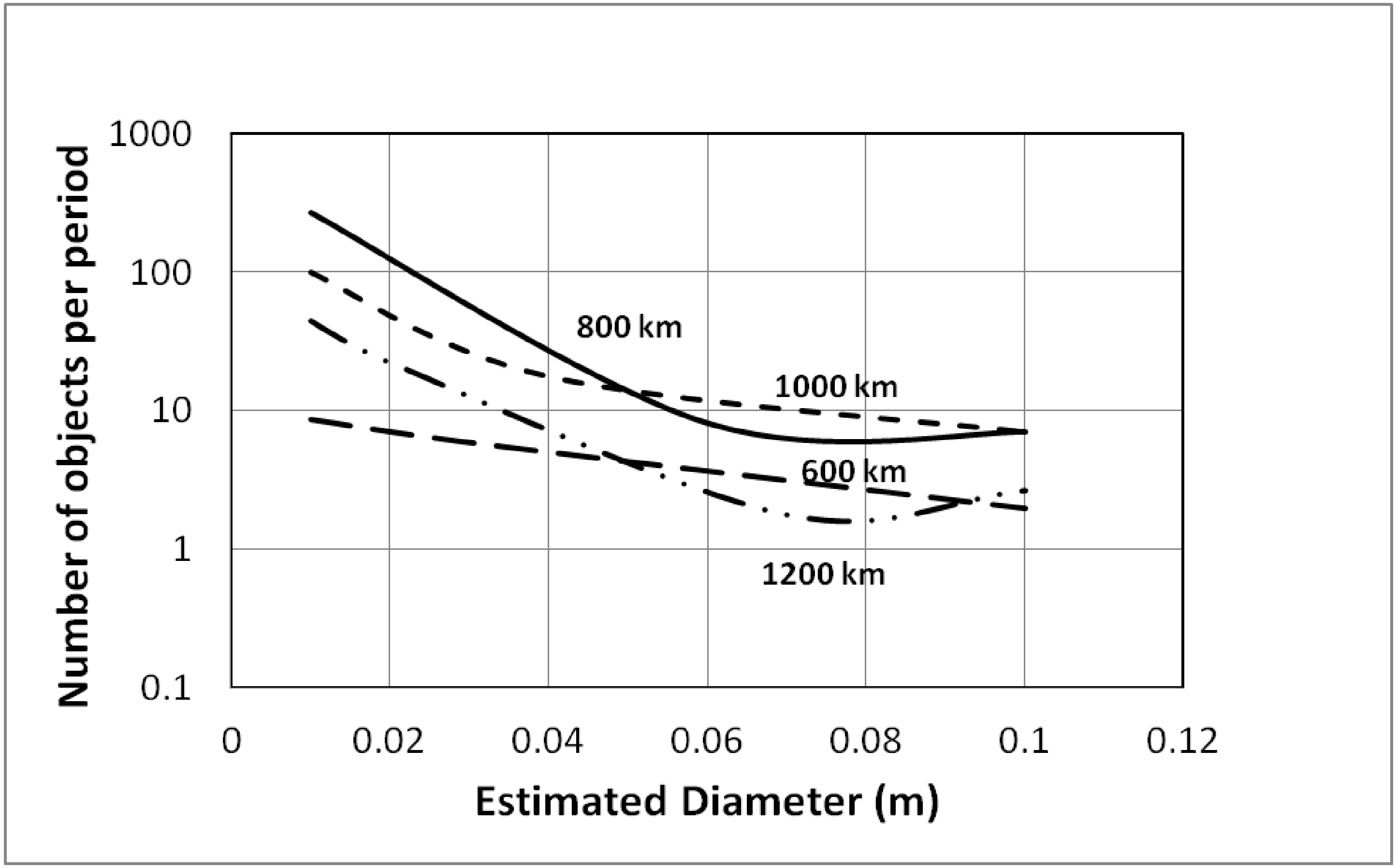
Small Debris Cataloging Association Criteria[20]

- The criteria to determine track status is associated with the comparison of the estimated position of the debris object with those in the catalog,
  - Catalog correlation occurs if the object is within the association volume
  - The association volume is estimated in radial (5km), in-track (3 sec) and out of plane direction (0.05deg)
- New UCTs will be compared to previous UCTs to determine which of the UCTs correlate to develop a catalog entry
  - The criteria for UCT correlation can be 3 to 4 times that for catalog correlation (e.g., 0.2 min in-track, 0.2 deg inclination)
- Current criteria were established primarily on the basis of detecting and tracking 10 cm to 1 meter objects and the nearest neighbor distance between these objects

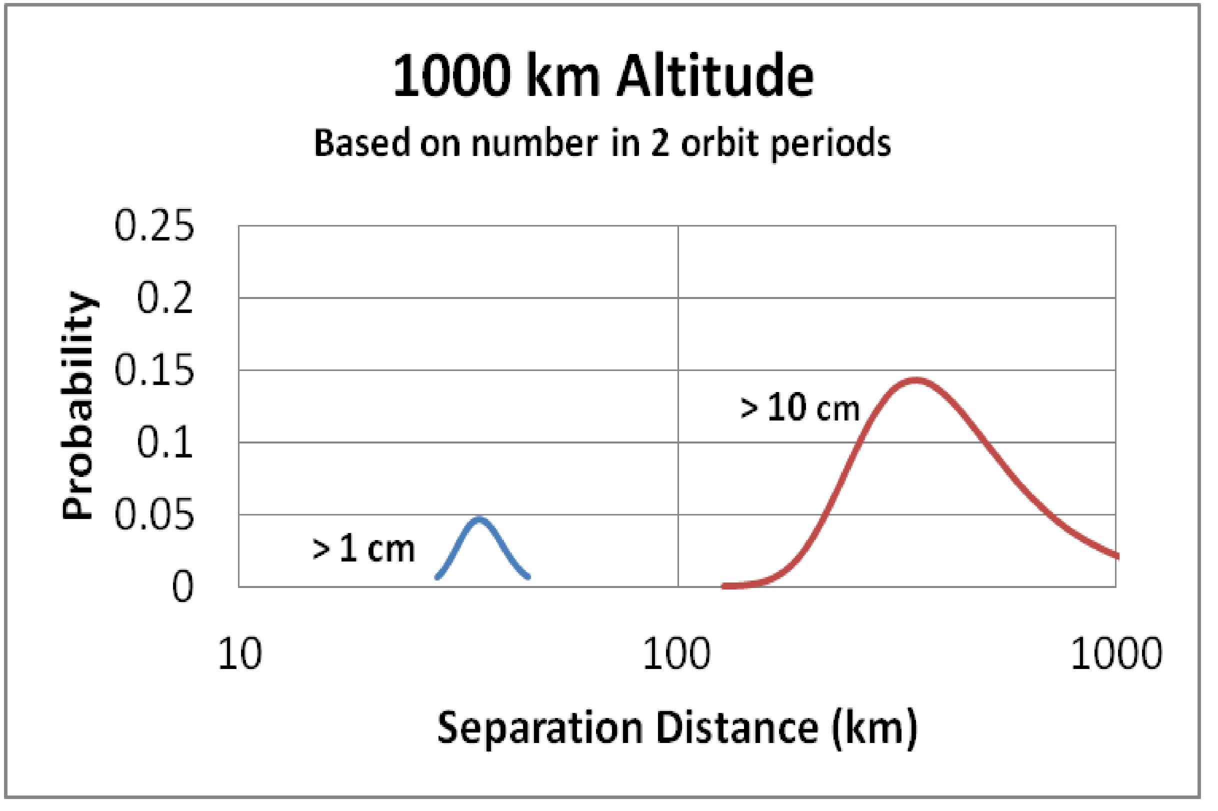
For the 1 to 10 cm population at the altitudes of interest association criteria needs to be assessed

Objects in a Single Pulse Search Cell

ORDEM 2000 Flux Data, 30º Lat, 45º El



Estimated Debris Object Separation
Poisson Probability Distribution



Current Radar Capability

- TIRA, Haystack and HAX dish radars have limited small debris track time capability in a fixed beam mode
  - With cuing the HAX radar with on-pulse modulation (LFM) and track times of 20 to 30 sec accurate track data can be provided on 3 cm objects at 1000 km
  - With cuing the Haystack radar can update all small (1 to 10 cm) debris UCT element sets
    - Requires on-pulse modulation and 30 sec track times
    - Provides 0.15 min period error and 0.02 deg inclination/node error on 1 cm object at 1000 km
  - With cuing and track times to 30 sec the L-Band TIRA can provide accurate track data on 3 cm objects at 1000km
- The Don-2N and FPS-85 phased array radars have the greatest potential to contribute uncued search and track data to a Space Debris Surveillance Network

Observations/Recommendations

- A future debris tracking radar should
  - Operate in the S-band to C-band
  - Have the sensitivity to detect/track 1 cm targets at 1800 km
  - Have agile beam capability to search and track 1 cm debris at 1800km, track to greater 60 sec
- A small debris catalog criteria needs to be assessed
  - Assess new small object UCT criteria for period, inclination and node for the 1 to 10 cm population
  - Utilize the existing radars to gather track data in the 2 to 5 cm region and exchange data to test cataloging algorithms
- The Proposed US Air Force S-band Space Fence Concept should meet the debris tracking radar requirements and form the main element of a Space Debris Surveillance network
  - If capable the ESA test radars, Monostatic (Spain) and Bistatic (France) could provide small debris track data
  - The Don-2N and FPS-85 have the potential to contribute to a Space Debris Surveillance Network
  - TIRA, Haystack and HAX can provide future RCS measurements and updates on established element set data

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