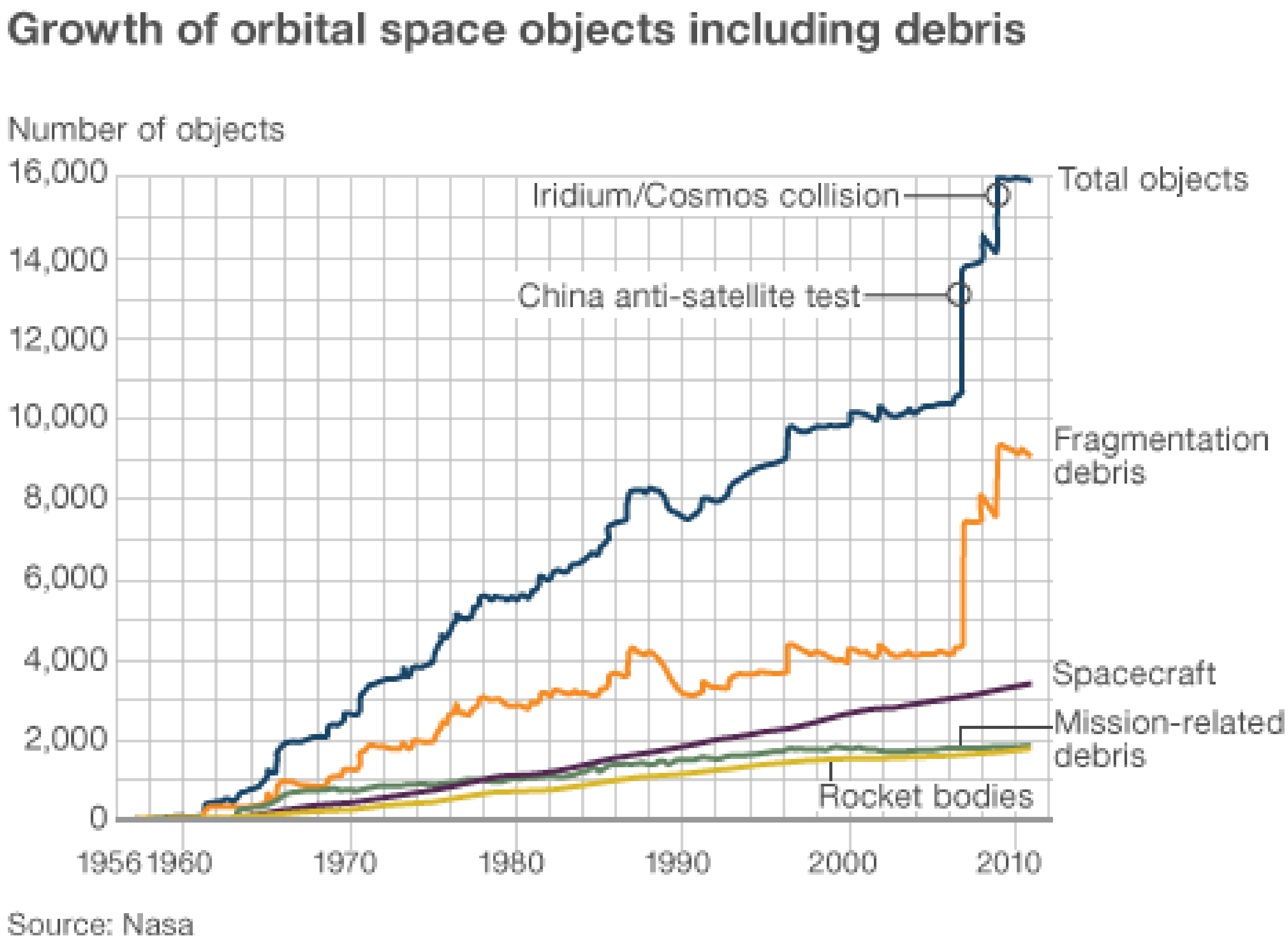
Bistatic Radar for space debris detection

- GRAVES is a French bistatic space surveillance system which was designed and built by ONERA.
- It officially became operational on 15 December 2005 and it is operated by the French Air Force.
- It provides 24 hours, seven days, detection and tracking of satellites and space debris flying over the French territory (and outside…)
- The LOFAR is a receiving station based in South England. It is run by the UK Science and Technology Facilities Council (STFC).
- The main function of the LOFAR station is to receive sky signals and select those of interest in time, frequency and spatial domain.
- **Aim is to investigate whether it is possible to exploit the GRAVES transmissions to passively detect and track satellites and space debris with the LOFAR receiver.**

Space debris



The GRAVES radar

- The GRAVES radar is a bistatic space surveillance system operated by ONERA
  - Transmitter located near Dijon, North-East
  - Receiver located near Apt, South-East
  - Baseline is about 400 km long

The GRAVES transmitter

- The transmitting antenna is made of 4 separate phased arrays of patched elements.
- Azimuthal coverage of 180 degrees towards the south hemisphere.
- 4 beams are present at the same time (one for each phased array) with a width of 7.5 degrees. The azimuth orientation of each beam is time-cycled to cover 45 degrees in 19.2 s. One step is 3.2 s.
- The beamwidth in elevation is 25 degrees to provide a coverage between 15 degrees and 40 degrees.

The GRAVES transmitter

A CW tone at 143.050 MHz is transmitted.

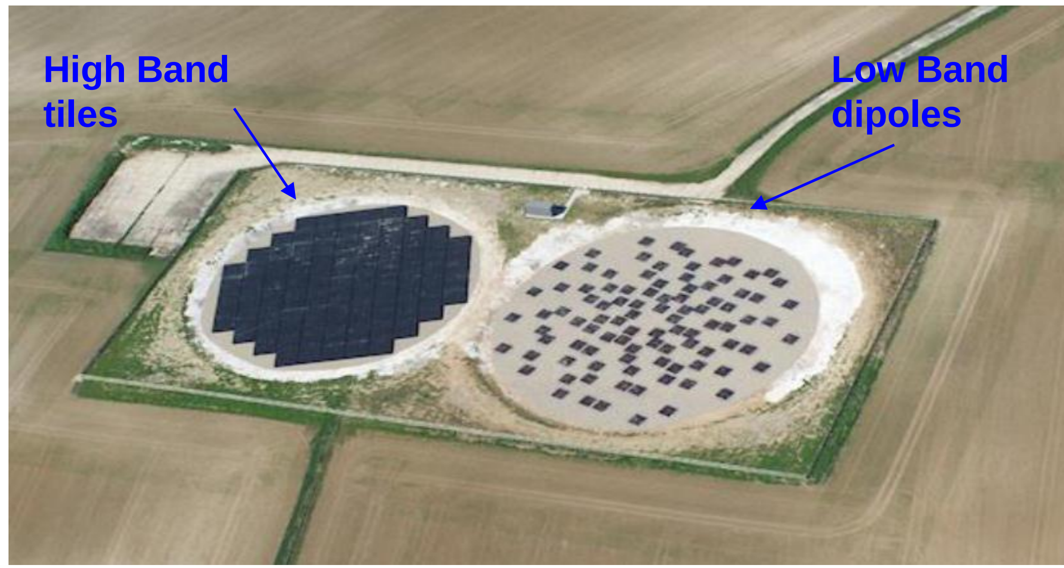
Unknowns:

- Transmitted Power
- Antenna Gain

The LOFAR receiver

- LOFAR is a STFC radio telescope located at Chilbolton observatory in Hampshire, South England.
- The antenna system consists of 96 low-band dipole elements to cover the bandwidth between 30-80 MHz.
- Plus 96 additional high-band tiles to cover the bandwidth 120-240 MHz.
- Each tile is made of a 4x4 array of dual-polarised crossed bow-tie dipoles.
- The system can form multiple simultaneous beams. For each bean the signal is digitised, recorded and can be processed offline.

The LOFAR receiver

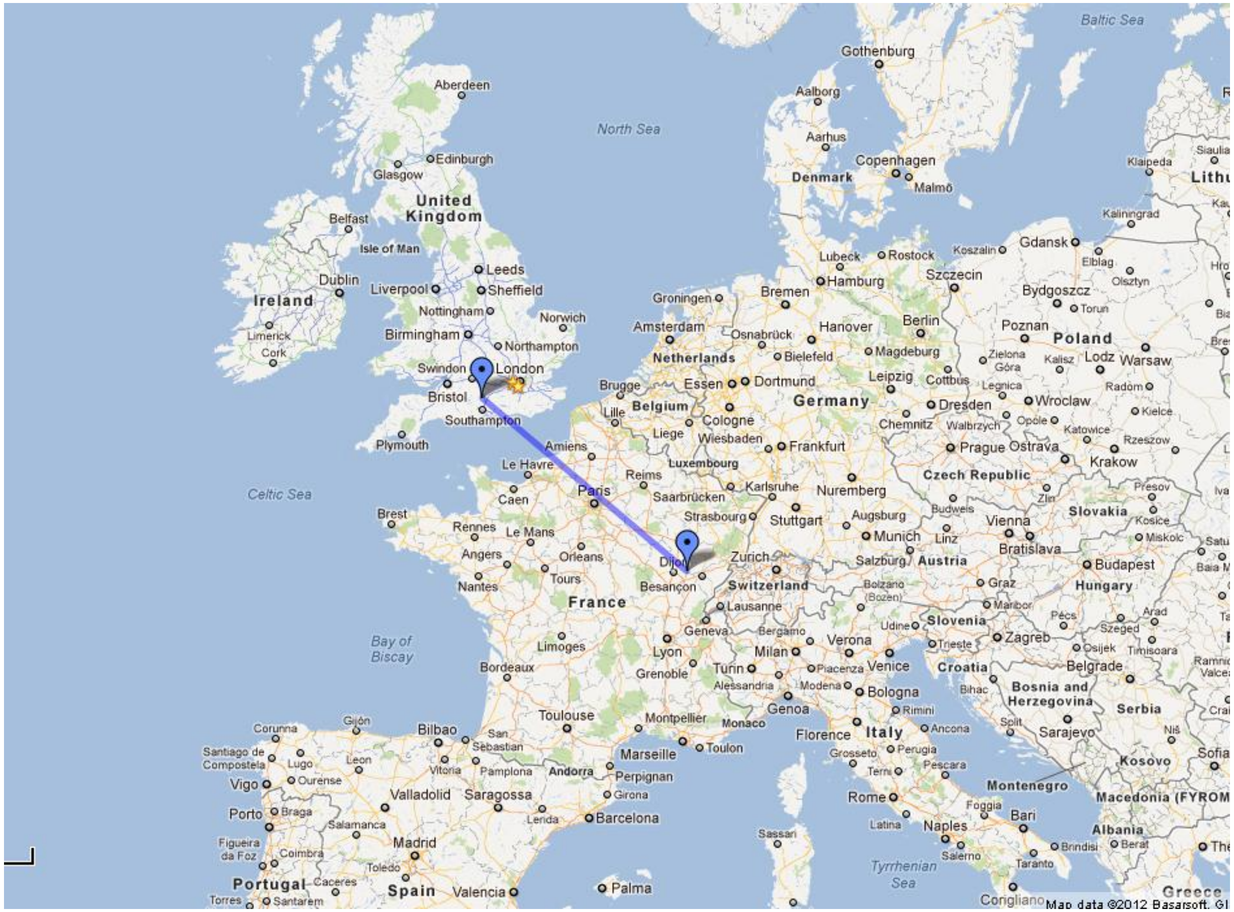


Receiver parameters

- The minimum effective area of each tile is 8 m^2, leading to a minimum gain of 13 dB.
- When all tiles are used an effective area of 1000 m^2 can be achieved.
- The receiver is sky-noise dominated and the noise temperature between 110 MHz and 190 MHz is about 395 K.

LOFAR-GRAVES system

- The baseline is about 427 km

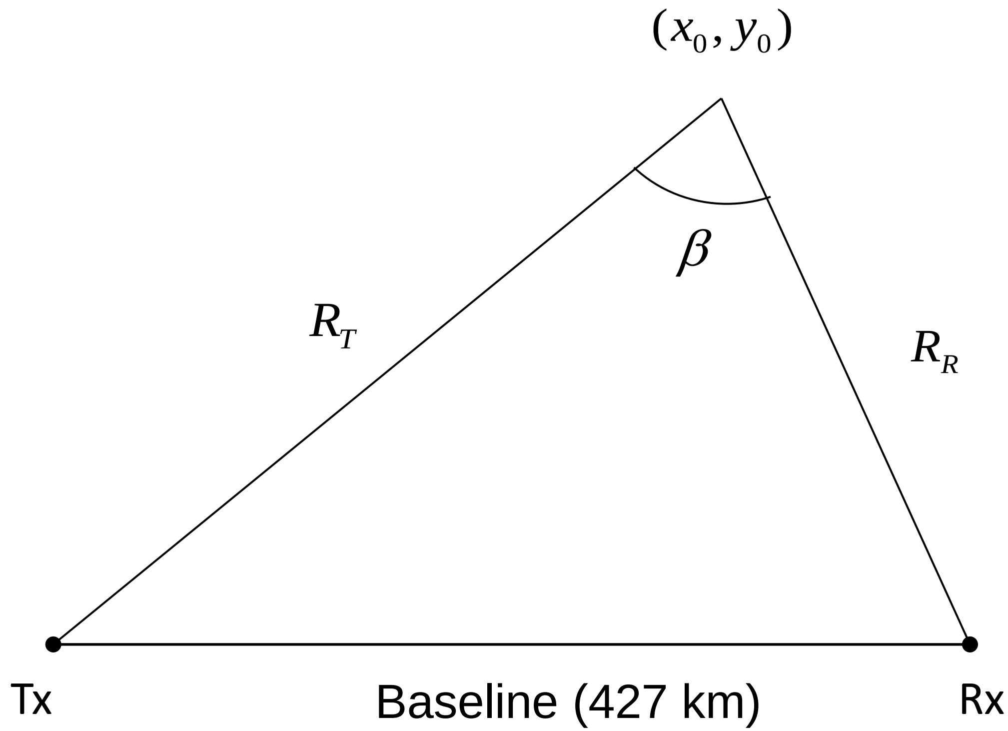


Bistatic range equation

$$P_R = \frac{P_T G_T A_e \sigma}{(4\pi)^2 R_T^{\,2} R_R^{\,2}}$$

$$P_n = T_{sky} K_b B$$

$$SNR = \frac{P_R}{P_n}$$

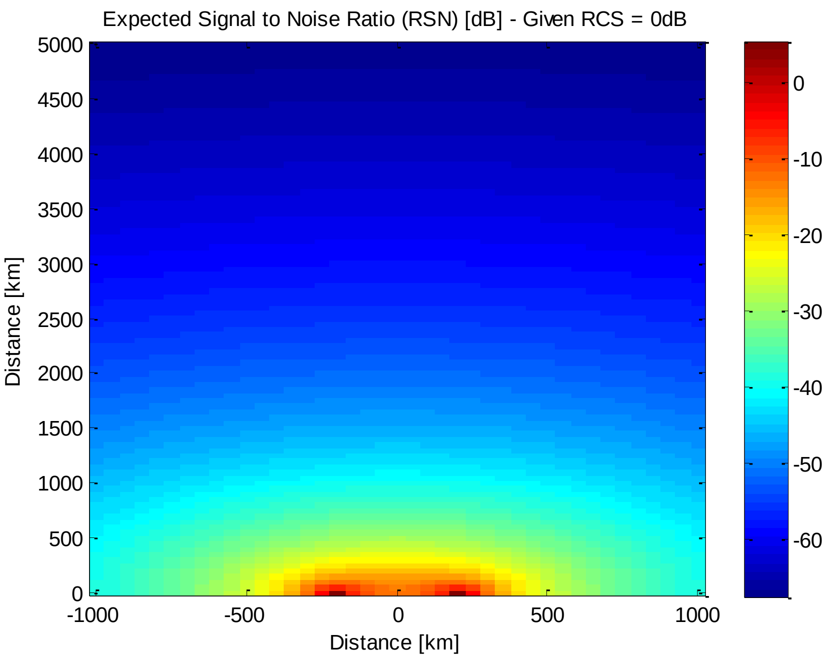


Bistatic range equation - simulations

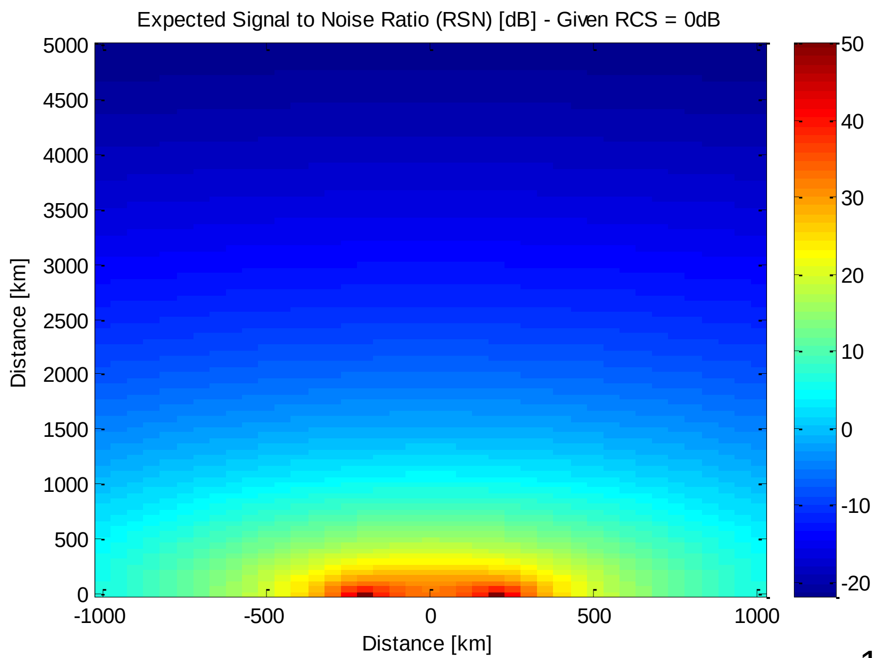
Under the assumption that:

$G_T = 30$ dB and $P_T = 1$ MW

B = 80 MHz

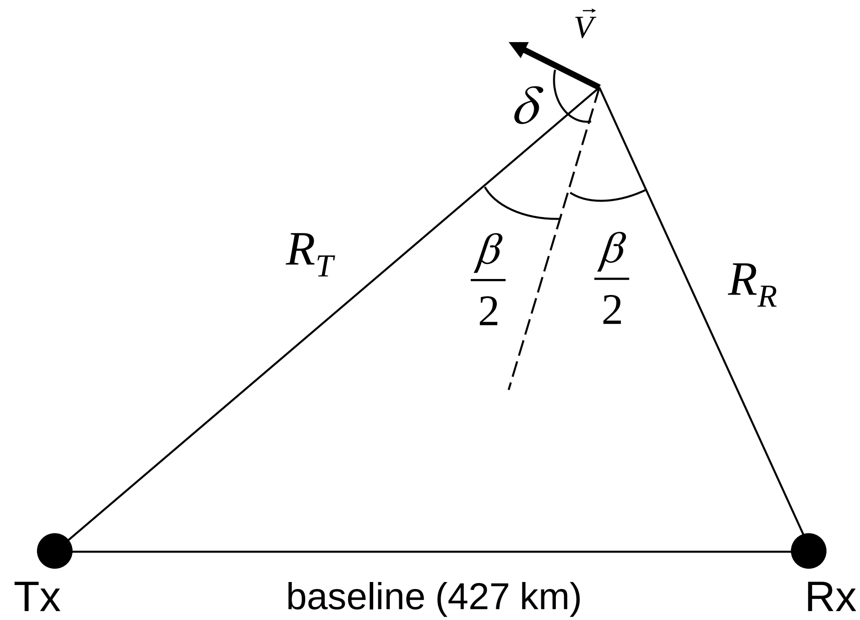


B = 2.4 kHz



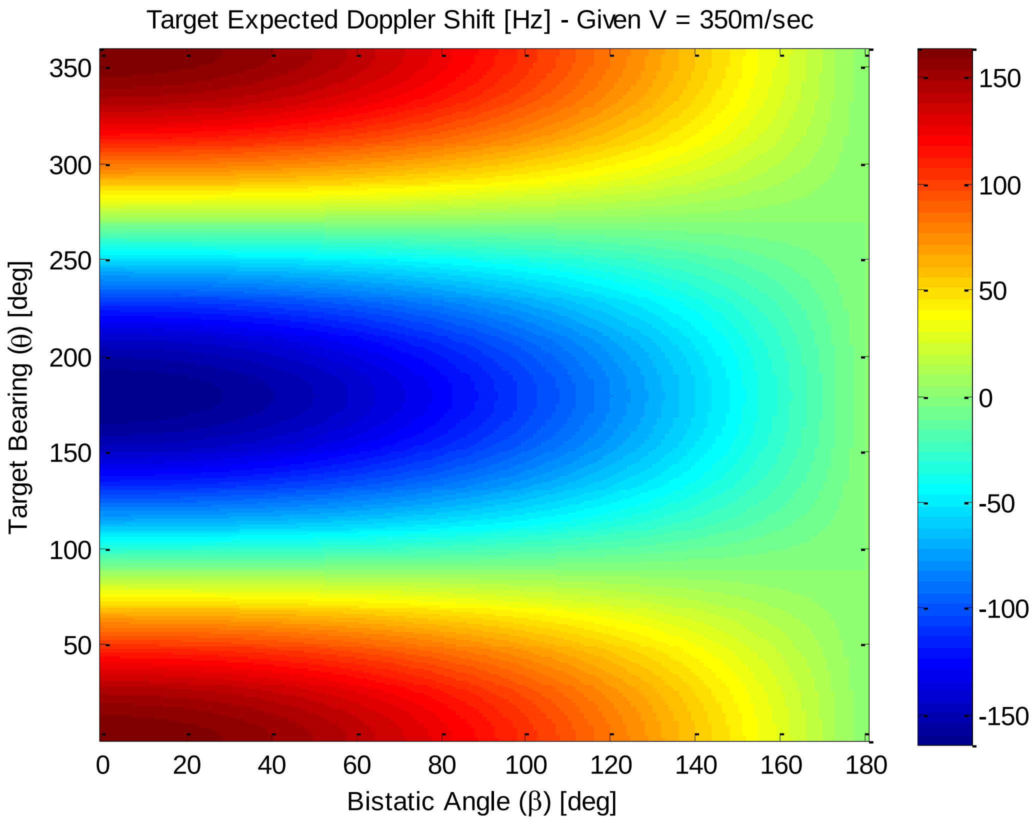
Bistatic Doppler

Given a target with a velocity $\vec{V}$, the bistatic Doppler shift depends on the geometry and the transmitted frequency only.



$$f_D = \frac{1}{\lambda}\left(\frac{dR_T}{dt} + \frac{dR_R}{dt}\right) = \frac{1}{\lambda}\left|V\right|\cos\left(\frac{\beta}{2}\right)\cos\delta$$

Expected Doppler - simulation



Preliminary experimental results

- VHF/UHF ground station consisting of receiving and transmitting equipment for the 144 MHz and 432 MHz bands
- Minimal loss of receiving performance at 143.050 MHz
- The receive antenna is a10-element crossed-Yagy array
- LNA optimised for 143 MHz (noise figure about 1 dB)
- Additional LNA (optimised for 144-146 MHz)
- Spectrum analyser to down convert to 10.69 MHz
- HF receiver for single sideband reception
- 2.4 kHz bandwidth
- Operator with headphone and spectral analysis (spectran)

VHF/UHF ground station

Lunar reflections

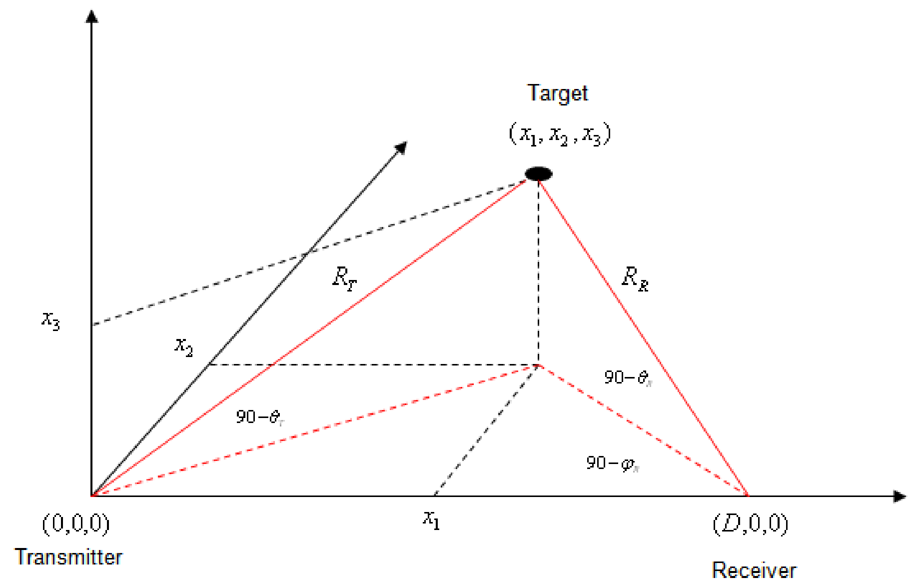
- The US Naval Observatory’s lunar position prediction software was used to determine the moon position.
- The observation time was chosen so that the moon was inside the beamwidth of both the GRAVES transmitter and receiver (22 February 2012 between 1430 and 1530 UTC).
- Spectran was used to detect any Doppler shifts.
- These were compared with the Doppler shifts predicted by the “EME Planner” software (monostatic approx)
- Weak signals 5 dB over the noise level were received in a 100 Hz bandwidth.
- At 15.09 UTC a Doppler shift of -215 Hz was measured. This matched the prediction by 5 Hz.
- Mean lunar orbit velocity is 1023 m/s. Distance from earth is 384,400 km.

NASA International Space Station

- The ISS is believed to be the satellite with the largest RCS.
- Online prediction by “Heaven Above” website.
- A pass at 1841 UTC on14th February 2012 was chosen.
- The satellite was on a SW to NE trajectory at a suitable elevation to guarantee a pass inside the GRAVES-LOFAR illuminated area.
- Expected Doppler shifts for the ISS can be between ±5 kHz.
- The received signal had the expected characteristics with a much larger bandwidth then the moon.
- It was present for about 3 seconds at a time and repeating with periods of about 20 s.
- The signal appeared outside the noise floor (B=2.4 kHz) and remained present for about 1.5 minutes.
- LEO (Perigee 387 km, Apogee 398 km). Average speed is 7,700 m/s.

Target tracking

The Doppler shift induced by a moving target can be expressed as a function of its position and velocity.



$$f_D = \frac{1}{\lambda}\left(\frac{dR_T}{dt} + \frac{dR_R}{dt}\right)$$

$$f_D = \frac{1}{\lambda}\left(\frac{x_1\dot{x}_1 + x_2\dot{x}_2 + x_3\dot{x}_3}{\sqrt{x_1^2 + x_2^2 + x_3^2}} + \frac{(x_1 - D)\dot{x}_1 + x_2\dot{x}_2 + x_3\dot{x}_3}{\sqrt{(x_1 - D)^2 + x_2^2 + x_3^2}}\right)$$

State equations

The target state *S(n)* is defined as the Cartesian co-ordinates of the target position and the target velocity.

Under the assumption that the target moves with a constant velocity (within integration time), the history of the target state can be written as an auto-regressive model (AR). The state at a time *n* is a linear combination of the state at *n-1* plus a motion perturbation.

$$S(n) = \begin{pmatrix} x_1(n) \\ \dot{x}_1(n) \\ x_2(n) \\ \dot{x}_2(n) \\ x_3(n) \\ \dot{x}_3(n) \end{pmatrix}$$

$$S(n) = \begin{cases} x_1(n) = x_1(n-1) + \dot{x}_1(n-1) * T \\ \dot{x}_1(n) = \dot{x}_1(n-1) + u_1(n) \\ x_2(n) = x_2(n-1) + \dot{x}_2(n-1) * T \\ \dot{x}_2(n) = \dot{x}_2(n-1) + u_2(n) \\ x_3(n) = x_3(n-1) + \dot{x}_3(n-1) * T \\ \dot{x}_3(n) = \dot{x}_3(n-1) + u_3(n) \end{cases}$$

$$S(n) = \begin{pmatrix} 1 & T & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & T & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & T \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} S(n-1) + \begin{pmatrix} 0 \\ u_1(n) \\ 0 \\ u_2(n) \\ 0 \\ u_3(n) \end{pmatrix}$$

$$S(n) = A * S(n-1) + W(n)$$

Measurement model

The LOFAR receiver measures the target Doppler shift, the elevation angle and bearing. The measurement vector can be expressed as a non-linear function of the target state *S(n)*. For example, if only a Doppler measurement is available

$$f_D(n) = g(S(n)) + V(n)$$

The equation can be approximated with a linear function using a Taylor series around the target state at *n-1*. The noise measurement *V*(*n*) is assumed to be a Gaussian process whose variance is related to the LOFAR Doppler resolution.

$$f_D(n) \simeq C(n, \hat{S}_{n-1}) * S(n) - C(n, \hat{S}_{n-1}) * \hat{S}_{n-1} + V(n)$$

with

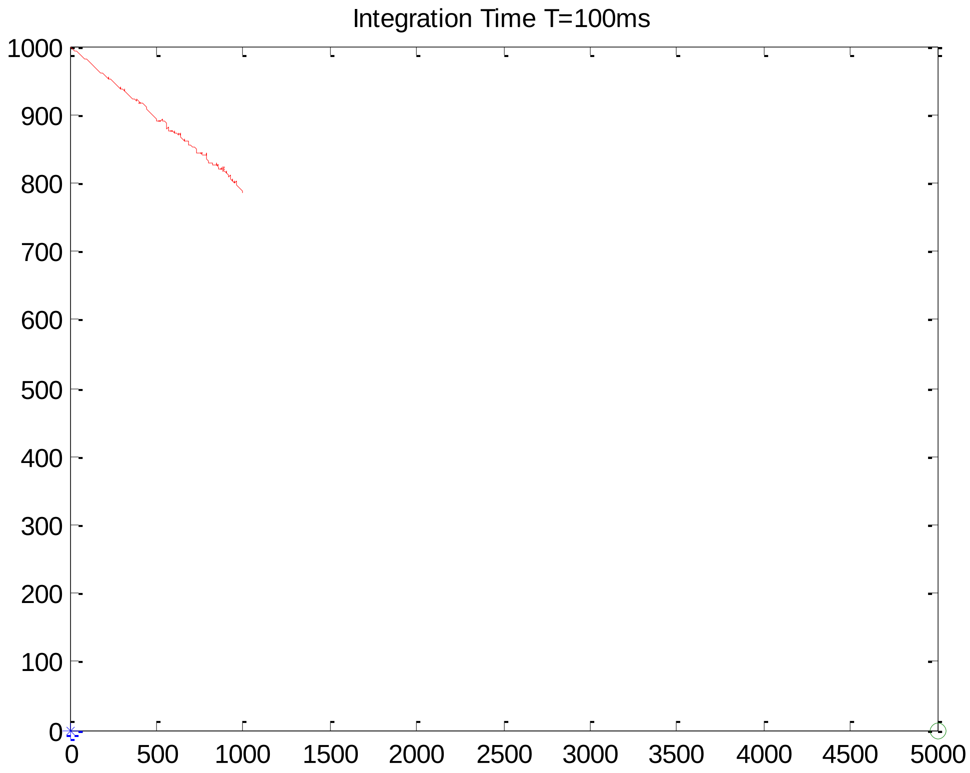
$$C(n, \hat{S}_{n-1}) = \left(\begin{array}{cccccc} \frac{df_D}{dx_1} & \frac{df_D}{d\dot{x}_1} & \frac{df_D}{dx_2} & \frac{df_D}{d\dot{x}_2} & \frac{df_D}{dx_3} & \frac{df_D}{d\dot{x}_3} \end{array} \right) \Bigg|_{\hat{S}(n-1)}$$

Results

The target state and target measurement equations can be used to implement a tracker that uses of a Kalman filter (Extended Kalman Filter).

Example

- Baseline 5 km
- Integration time *T*= 100 ms
- Target position at n=0 is (0,0, 1km)
- Initial velocity (-2 m/s,0, -10 m/s)



Results: GRAVES/LOFAR geometry

Example

- Baseline 427 km
- Integration time *T*= 100 ms
- Target position at n=0 is (0,0,400km)
- Initial velocity (-7000 m/s,0,-2 m/s)

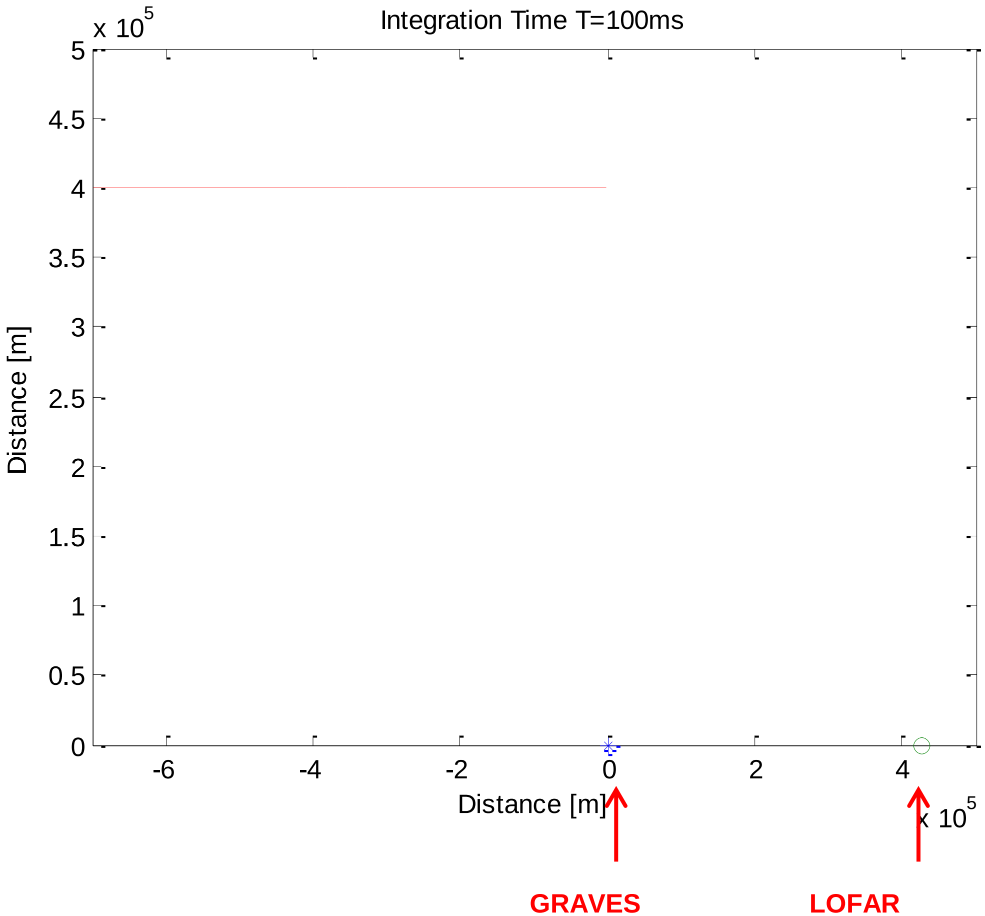
The tracker nicely follows the target trajectory.

Cons

1) Input target trajectory is the theoretical one plus white noise.
2) The initial state is assumed known.

Pros

1) Perturbations are accounted for by the tracker.
2) Only Doppler information has been used.



Conclusions and future work

- Lunar observation measurements strongly suggest that the received signal was indeed caused by reflections from the moon.
- The measured SNR was lower than expected but this was probably due to the presence of additional noise sources in the control room.
- Detection measurements of the ISS corroborated these hypotheses.
- Results suggest that if the receive bandwidth and the spectral analysis are optimised, it should be possible to detect objects with an RCS some 25 dB lower than that of the ISS.
- Much more promising results are expected with the actual LOFAR receiver due to its greater sensitivity.