Atmospheric Radar for Space Debris Detection

by
Adila W Tire

NASSP: UKZN node

June 2, 2016

Outline

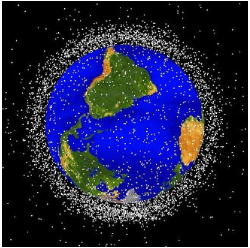
Introduction and Motivation

Space Debris?

-Space junks, no longer have any use

-the remainders of human space activity, satellites

-are potential problems for the ongoing space science and technology



(model figure)

Int. Cont..

Object count:

Since Sputnik 1957 (Russia),

-there are about 1100 operational and 2600 not(Big junks)

-Half of operational satellites operate in the Lower-Earth Orbit about 100km above the surface, like ISS, HST and many more are in LEO

-this is where space debris are more dangerous, small objects here move very fast (6 to 8 km per second)

-in GEO object move almost with the same speed, have more stable orbit $\Rightarrow$ no or less distractive collision

-LEO is the most crowded region with operational satellites and space debris,less stable orbit and higher relative speed $\Rightarrow$ a greater hazard (eg. French Cerise satellite)

Int. Cont...

-Increase in space debris also can make space travel more dangerous
-There are about 21,000 objects larger than 10cm (NASA and DoD track these objects)
-Estimated 100s of thousands between 1 to 10cm size
-and 10s of millions are less than 1cm
Ground-based space debris measurement can be optical or radar
* Detecting, measuring, tracking and imaging all these objects is a big challenge and expensive since the damage debris could inflict is huge $\Rightarrow$ no exemption
** This motivates people to search for alternative and easy means of space debris measurements

Int. Cont...

Since atmospheric signals contain signals scattered from space debris on top of signals scattered from the atmosphere
-atmospheric signals could be used for Space Debris measurements
-perhaps, alternative measurement
** Aim: to model the transmitted and received signals and detect small-size space debris in the presence of white noise.

Radar overview

Radar

– RAdio Detection And Ranging, employs refection of radio wave (Electromagnetic wave) used in Defence, meteorology, early warning systems, mapping, traffic control...

Frequency:

3MHz(HF) to 40GHz(Ka-band), $>$34GMz(MMW)

Parts: antenna, duplexer, oscillator, mixers, filter, amplifier, waveform generator, and signal processor.

Radar Equation

Radar Equation

The power receive by the Radar, Radar equation is given by:

$$P_{Dr} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} \tag{1}$$

where P_t is transmitted power, G is antenna gain, λ is wavelength, σ is radar cross section and R is distance

If S_{min} is the minimum detectable signal at the receiver, the maximum radar distance will be

$$R_{max} = \left(\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{min}} \right)^{1/4} \tag{2}$$

Radar Cont...

The signal-to-noise ratio (SNR) at the output defined by,

$$SNR = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 k T_e BFLR^4} \quad (3)$$

where $k = 1.38 \times 10^2 3J/K$ $(Boltzman\ constant)$, T_e is effective noise temperature, B is radar band width (Frequency), F is noise of the receiver and L is total radar losses

Ambiguity Function

Radar Ambiguity Function

- used to study the effectiveness of radar waveform for various radar application, to determine range and speed(Doppler shift) resolution

For a signal $s(t)$ the energy of radar signal is

$$E = \int_{-\infty}^{\infty} \mid s(t) \mid^2 dt \tag{4}$$

The 2D correlation function from matched filter response is

$$\chi(\tau; f_d) = \int_{-\infty}^{\infty} s(t)s^*(t+\tau)exp(j2\pi f_d t)dt \tag{5}$$

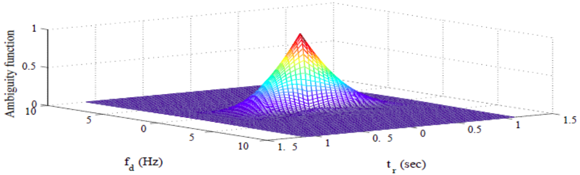
where τ is the time delay and f_d is the Doppler frequency shift due to the motion the target.

Amb. Cont...

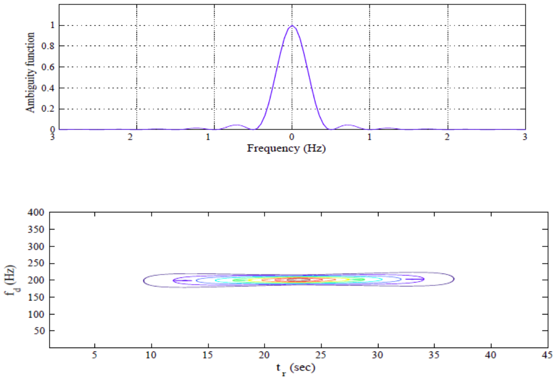
Then using the correlation function *equation* (5) for a normalized rectangular pulse $s(t) = \frac{1}{\sqrt{\tau'}} Rect\left(\frac{1}{\tau'}\right)$

$$|\chi(\tau; f_d)|^2 = |\left(1 - \frac{|\tau|}{\tau'}\right) \frac{sin(\pi f_d(\tau' - |\tau|))}{\pi f_d(\tau' - |\tau|)}|^2 \qquad (6)$$

is the ambiguity function of the radar and it is practically a form of *Sinc function* $sin(x)/x$ (the 3D plot)



Amb. Cont...



The upper panel is the cross-section and bottom is the couture plot of the corresponding ambiguity function

Detection Using Atmospheric Radar

Modelling Radar Measurement

For a pulse radar with transmission modulation envelop $env(t)$ the transmitted signal of the radar is given by,

$$s_t(t) = env(t).exp(i\omega_r t) \tag{7}$$

The received signal from a point target at a distance of R_o reaching just at the antenna will be,

$$s_r(t) = A_o.s_t(t - 2R_o/c) \tag{8}$$

where A_o is a constant depending on attenuation, c is speed of electromagnetic wave

Det. Cont...

With a mixing signal $exp(-i\omega_1 t)$ the signal become,

$$s_{rt}(t) = A_o.env(t - 2R_o/c).exp(i\omega_t).exp(-i\omega_r 2R_0/c) \quad (9)$$

where $\omega_t = \omega_r - \omega_1$
If $h(t)$ is the impulse response of the matched filter of the receiver, the signal become the convolution of the two,

$$s(t) = A_o.h(t) * env(t - 2R_o/c).exp(i\omega_t).exp(-i\omega_r(2R_o/c)) \quad (10)$$

Assume that during the beam passage the target has constant radial acceleration a_o. From the equation of motion.

$$R(t) = R_o + v_o t + \frac{1}{2}a_o t^2 \quad (11)$$

where R_o is initial range and v_o is initial speed (at $t = 0$)

Det. Cont...

For a slowly moving target during the beam passage, we can replace $R(t)$ by R_o, the signal become

$$s(t) = A_o.h{*}env(t - \frac{2}{c}R(t)).exp(-i\omega_r \frac{2R_o}{c}).exp(-i\omega_o t).exp(-i\alpha_o t^2) \quad (12)$$

where $\omega_o = 2v_o\omega_r/c$ and $\alpha_o = a_o r/c$

Considering Noise:

The signal contain noise(random variable, $n(t)$) may be given by,

$$m(t) = s(t) + n(t) \quad (13)$$

Assuming Gaussian noise (noise is random)-the mean value is zero and it has some variance $\sigma^2/2$ and the probability density $D(n)$ is

$$D(n) = \frac{1}{\pi\sigma^2}.exp(-\frac{1}{\sigma^2|n|^2}) \quad (14)$$

Det. Cont...

The autocorrelation of the noise is

$$\bar{n}_i(t) = \int_{-\infty}^{\infty} n_i^*(t) n_i(t+\tau^{'}) d\tau^{'} = \frac{N_o}{2}\delta(t) \qquad (15)$$

$\Rightarrow$ the noise samples $n_k = n(k\tau)$ for the maximum sampling interval τ are not correlated
The joint conditional probability density is

$$D(m_k|s_k) = \frac{1}{\pi\sigma^2} exp(-\frac{1}{\sigma^2}|m_k - s_k|^2) \qquad (16)$$

For a sampling measurements $m_k = m(k\tau)$

Matched Filter

Matched Filter

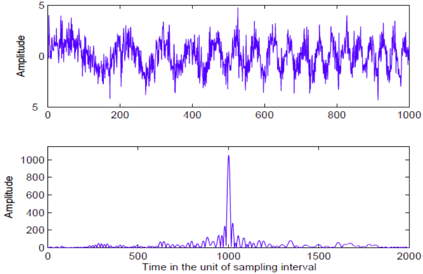
Matched filter is characterized by high signal-to-noise ratio (SNR). For received signal $s(t)$, the frequency-response function of a linear, time invariant filter which maximizes the output SNR is

$$H(f) = S^*(f) \tag{17}$$

where $S(f)$ is the Fourier transform of $s(t)$ and $*$ indicate the complex conjugate.
The filter whose frequency-response given by *equation*(17) is Matched filter

Mat. Cont...

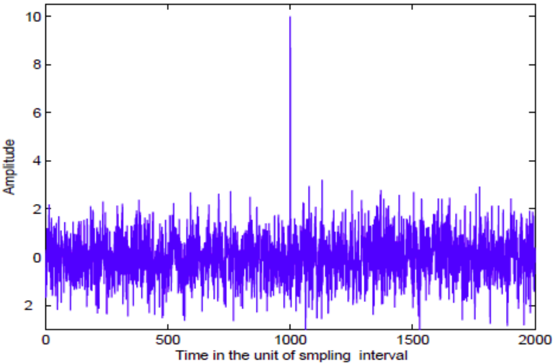
For unknown received signal which is accompanied by white noise, the impulse response of the matched filter is assumed to be the replica $h(t) = s^*(-t)$



(The signal with white noise and its corresponding matched filter)

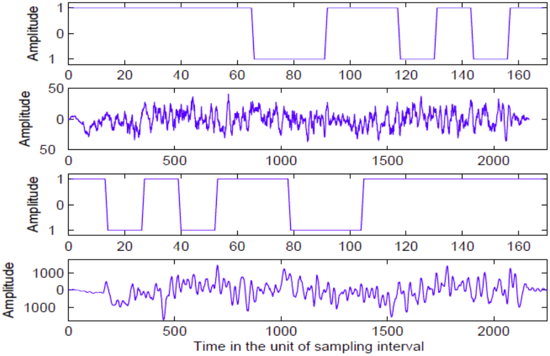
Big Debris

For a very big target (big enough to dominate the corresponding random noise), the matched filter simulation results



Small Debris

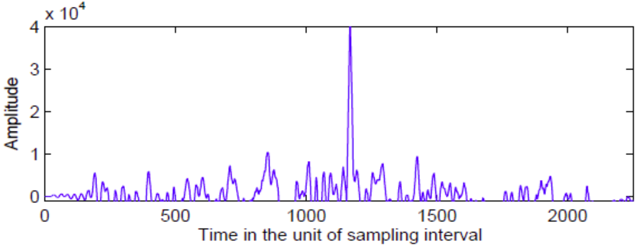
Applying the same technique for a small size debris no object could be detected.



Small Debris Detected

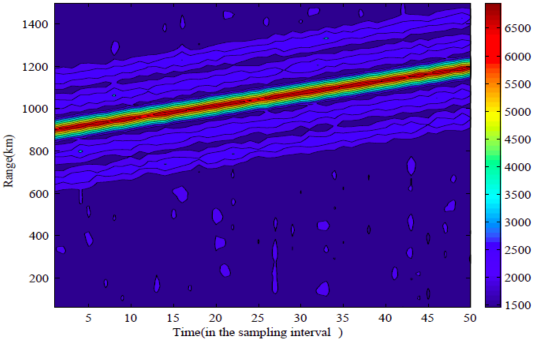
Small Debris Detected

In such case, it is common to sum up some successive pulses:
-signal from atmosphere (white noise) goes to zero $\Rightarrow$ suppressed
-signal from small debris (not random) sustains $\Rightarrow$ amplified



Small Debris Detection

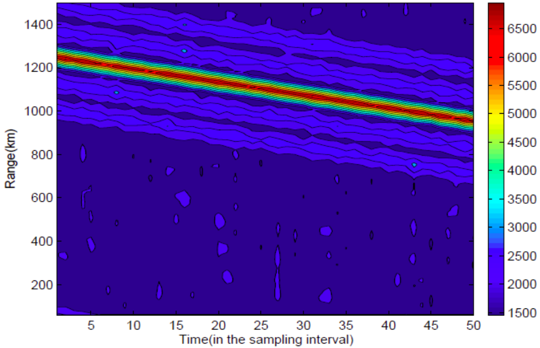
Evolution of space debris with range and time



(Debris detected as it moves away)

Small Debris Detection

Evolution of space debris with range and time



(Debris detected as it approaches)

Summery

-Since the back scattered signals from the atmosphere contain scattered signals form space debris too
-Both big and small size could be detected
-Since atmospheric radars are not meant for space debris detection, perhaps it is a cheep way to deal with space debris detection

Geomagnetic Storms

Geomagnetic Storms

-Geomagnetic storms are perturbations of Earth's magnetic field which shield the Earth from energetic particles

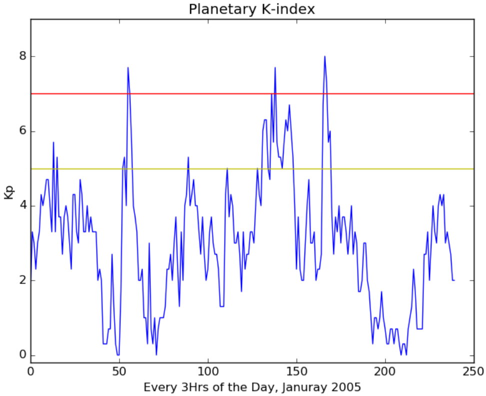
-The storms appear due to a coronal mass ejection(CME) or a high speed/energy solar wind stream pass over the Earth.

-Storms determined/evaluated by the magnetic indices, there are a number of magnetic indices, such as Kp and Dst

-**Kp (planetary index)** measures the deviation of the most perturbed horizontal component of the Earth's magnetic field in some selected observatories worldwide, the average every 3 hour

-it has quasi-logarithmic scale from 0 to 9

Geomagnetic Storms

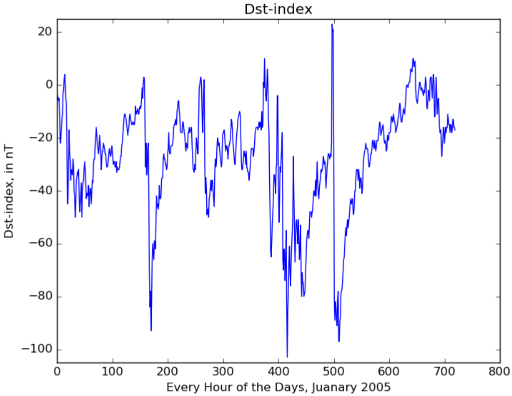


(Kp-index, data from OMNI2web)

Year: '2005' Day: '7' Time: 21.0 Kp index: 7.7
Year: '2005' Day: '8' Time: 0.0 Kp index: 7.0
Year: '2005' Day: '18' Time: 0.0 Kp index: 7.0
Year: '2005' Day: '18' Time: 6.0 Kp index: 7.7
Year: '2005' Day: '21' Time: 18.0 Kp index: 8.0
Year: '2005' Day: '21' Time: 21.0 Kp index: 7.3

-**Dst(Disturbance Storm-time index)** measures the depression of horizontal magnetic field by enhancement of the westward magnetospheric equatorial ring current.

Geomagnetic Storms



(Dst-index, data from OMNI2web)

Thanks

Thank you all!