

# From a Different Perspective : Principles, Practice and Potential of Bistatic Radar

H. D. Griffiths

Bistatic radar systems have been studied and built since the earliest days of radar. They have the advantages that the receivers are passive, and hence undetectable. The receiving systems are also potentially simple and cheap. Bistatic radar may have a counter-stealth capability, since target shaping to reduce monostatic RCS will in general not reduce the bistatic RCS. In spite of those advantages, rather few bistatic radar systems have got past the 'technology demonstrator' phase. It has also been remarked that activity in bistatic radar tends to vary on a period of approximately fifteen years, and that currently we are at a peak of that cycle; there is particular current interest in passive coherent location (PCL) techniques, using broadcast and communications signals as 'illuminators of opportunity'.

This paper presents a review of some of the history, and the properties and current developments in the subject, and conjectures whether or not the present interest is just another peak in the cycle.

*Index Terms*— bistatic radar, passive coherent location.

## I. INTRODUCTION

Bistatic radar systems have been studied and built since the earliest days of radar. As an early example, the Germans used the British Chain Home radars as illuminators for their *Klein Heidelberg* bistatic system. Bistatic radars have some obvious advantages. The receiving systems are passive, and hence undetectable. The receiving systems are also potentially simple and cheap. Bistatic radar may also have a counter-stealth capability, since target shaping to reduce target monostatic RCS will in general not reduce the bistatic RCS. Furthermore, bistatic radar systems can utilize VHF and UHF broadcast and communications signals as 'illuminators of opportunity', at which frequencies target stealth treatment is likely to be less effective.

Bistatic systems have some disadvantages. The geometry is more complicated than that of monostatic systems. It is necessary to provide some form of synchronization between transmitter and receiver, in respect of transmitter azimuth angle, instant of pulse transmission, and (for coherent

processing) transmit signal phase. Receivers which use transmitters which scan in azimuth will probably have to utilize 'pulse chasing' processing.

Over the years a number of bistatic radar systems have been built and evaluated. However, rather few have progressed beyond the 'technology demonstrator' phase. Willis [32] has remarked that interest in bistatic radar tends to vary on a period of approximately fifteen years, and that currently we are at a peak of that cycle.

The purpose of this paper is therefore to present a subjective review of the properties and current developments in the subject, with particular emphasis on 'passive coherent location' and to consider whether or not the present interest is just another peak in the cycle.

## II. PROPERTIES OF BISTATIC RADAR

### A. Bistatic radar geometry

The properties of bistatic radar are described in detail by Willis [30, 31] and by Dunsmore [6]. Jackson [17] has analyzed the geometry of bistatic radar systems, and his notation has been widely adopted.

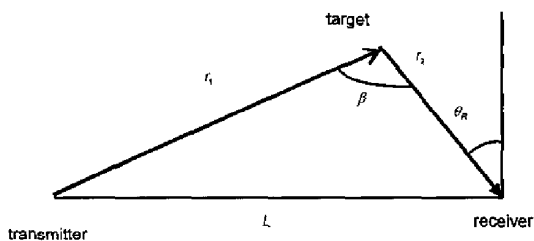


Figure 1. Bistatic radar geometry.

From this:

$$r_2 = \frac{(r_1 + r_2)^2 - L^2}{2(r_1 + r_2 + L \sin \theta_R)} \quad (1)$$

Contours of constant bistatic range are ellipses, with transmitter and receiver as the two foci.

H. D. Griffiths is with the Department of Electronic and Electrical Engineering, University College London, Torrington Place, London, WC1E 7JE, UK (h.griffiths@ee.ucl.ac.uk)

The bistatic radar equation is derived in the same way as the monostatic radar equation:

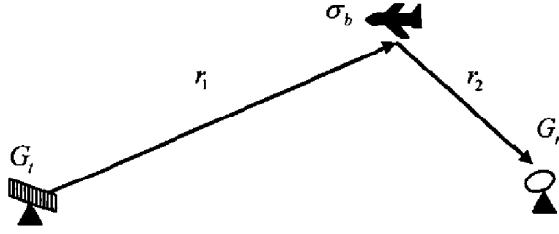
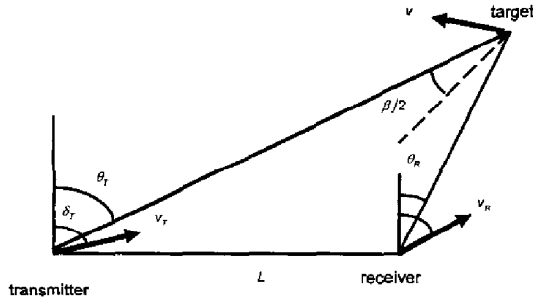


Figure 2. Bistatic radar equation.

$$\frac{P_r}{P_n} = \frac{P_t G_t G_r \lambda^2 \sigma_b}{(4\pi)^3 r_1^2 r_2^2 k T_0 B F} \quad (2)$$

The factor  $1/(r_1 r_2)$ , and hence the signal-to-noise, has a minimum value for  $r_1 = r_2$ . Thus the signal-to-noise ratio is highest for targets close to the transmitter or close to the receiver.

Doppler shift depends on the motion of target, transmitter and receiver (Figure 3), and in the general case the equations are quite complicated [17, 31].



$$\beta = \theta_t - \theta_r$$

Figure 3. Bistatic Doppler (after Jackson [17]).

In the case when only the target is moving the Doppler shift is given by:

$$f_D = \left( \frac{2V}{\lambda} \right) \cos \delta \cos(\beta/2) \quad (3)$$

#### B. Bistatic radar cross section

The bistatic RCS of targets has been studied extensively [7], though relatively little has been published in the open literature. Early work [4, 18] resulted in the bistatic

equivalence theorem, which states that the bistatic RCS  $\sigma_b$  is equal to the monostatic RCS at the bisector of the bistatic angle  $\beta$ , reduced in frequency by the factor  $\cos(\beta/2)$ , given (i) sufficiently smooth targets, (ii) no shadowing, and (iii) persistence of retroreflectors. These assumptions are unlikely to be universally valid, particularly for stealthy targets, so the results should be used with care.

#### C. Forward scatter

A limiting case of the bistatic geometry occurs when the target lies on the transmitter-receiver baseline. Whilst this means that range information cannot be obtained, the geometry does give rise to a substantial enhancement in scattering, even for stealthy targets, due to the forward scatter phenomenon. This may be understood by reference to Babinet's principle, which shows that a perfectly absorbing target will generate the same forward scatter as a target shaped hole in a perfectly conducting screen. The forward scatter RCS is approximately  $\sigma_b = 4\pi A^2 / \lambda^2$ , where  $A$  is the target projected area, and the angular width  $\theta_b$  of the scattering will be of the order of  $\lambda/d$  radians, where  $d$  is the target linear dimension. Figure 4 shows how these vary with frequency, for a target of the size of a typical aircraft, and shows that frequencies around VHF / UHF are likely to be optimum for exploiting forward scatter.

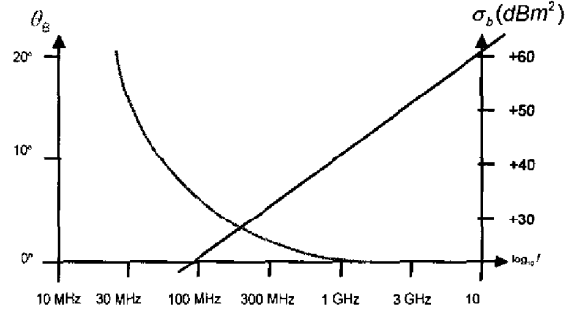


Fig. 4. Variation of forward scatter RCS and angular width of response ( $d = 10\text{m}$ ,  $A = 10\text{m}^2$ ).

#### D. Bistatic clutter

Bistatic clutter is subject to greater variability than the monostatic case, because there are more variables associated with the geometry [30]. The clutter RCS  $\sigma_c$  is the product of the bistatic backscatter coefficient  $\sigma_b^0$  and the clutter resolution cell area  $A_c$ . Both  $\sigma_b^0$  and  $A_c$  are geometry dependent, with the maximum value of  $\sigma_b^0$  occurring at specular angles. There is relatively little experimental data available, and little work has been done in developing models for bistatic clutter.

There is some reason to suppose that bistatic sea clutter may be less 'spiky' than equivalent monostatic sea clutter, and hence that bistatic geometries may be more favourable for detection of small targets – but this remains to be investigated.

There is thus much scope for new work on bistatic clutter; to gather data, to analyze the results, and to develop bistatic clutter models.

### III. PASSIVE COHERENT LOCATION

The use of broadcast or communications signals as ‘illuminators of opportunity’ has become known as ‘passive coherent location’ (PCL) or ‘hitchhiking’, and there has been particular interest in this aspect of bistatic radar in recent years.

The properties of transmissions for these purposes can be assessed in terms of (i) power density at the target, (ii) spatial and temporal coverage, and (iii) waveform. The power density  $\Phi$  (in  $W/m^2$ ) at the target is evaluated from:

$$\Phi = \frac{P_t G_t}{4\pi r^2} \quad (4)$$

The spatial and temporal coverage will depend on the location of the transmitter, its radiation pattern, and (for example) whether it is stationary or moving and whether it operates for 24 hours per day or not. In some cases the vertical plane radiation pattern of TV or radio transmissions is deliberately shaped so as to avoid wasting power above the horizontal.

The coverage achieved by VHF FM radio and TV transmissions is substantial. This is because such systems have to be designed to cope with non line-of-sight propagation and very inefficient antenna and receiver systems. Cellphone base stations are also potentially useful as PCL illuminators [33, 35]; whilst these are of rather lower power, there are many of them, especially in urban areas. Satellite-borne illuminators, such as DBS TV [12], satellite communications and navigation [2, 19] and spaceborne radar [13, 23, 34] are also of interest.

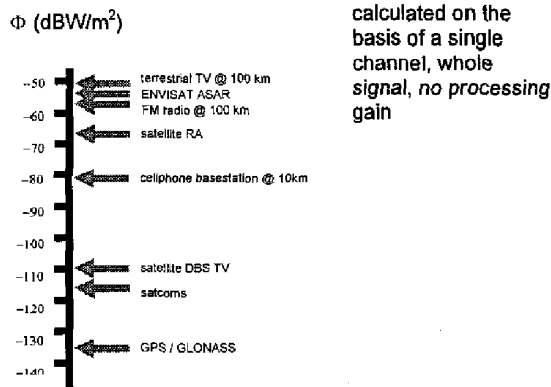


Fig. 5. Power density  $\Phi$  for various PCL illuminators.

The waveform parameters of interest are the frequency, bandwidth, ambiguity function, and stability. In some cases it may be appropriate only to use a portion of the available signal (for example, to avoid ambiguities associated with the line and frame repetition rate of analogue TV modulation). In such cases the transmit power value used in equation (4) should be appropriate.

Figure 5 shows the values of  $\Phi$  for various PCL illuminators, under various assumptions. These are calculated on the basis of a single channel, the whole signal bandwidth, and no processing gain.

The detection performance can then be estimated from:

$$(r_2)_{\max} = \left( \frac{\Phi \sigma_t \lambda^2 G_p}{(4\pi)^2 (S/N)_{\min} k T_0 B F} \right)^{1/2} \quad (5)$$

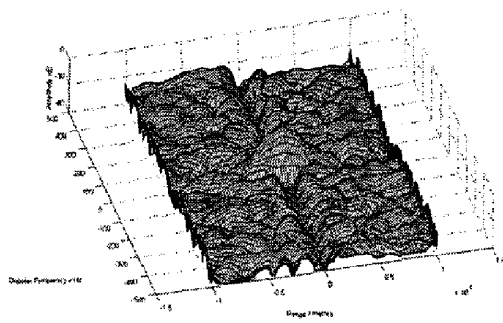
where  $G_p$  is the processing gain, which is the product of the waveform bandwidth and the integration dwell time. The integration dwell time in turn depends on the waveform coherence and the target dynamics. As a rule of thumb, the maximum integration dwell time is given by:

$$T_{\max} = \left( \frac{\lambda}{A_r} \right)^{1/2} \quad (6)$$

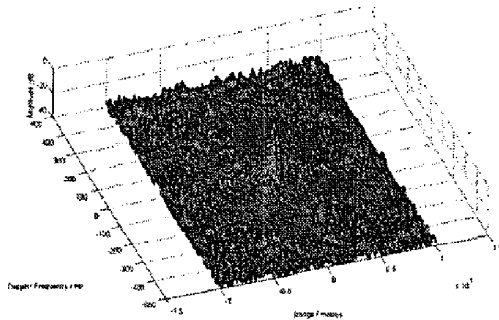
where  $A_r$  is the radial component of target acceleration. From these equations the coverage can be predicted in terms of Ovals of Cassini around transmitter and receiver.

The waveform properties of a variety of PCL illuminators (VHF FM radio, analogue and digital TV, digital audio broadcast (DAB) and GSM at 900 and 1800 MHz) have been assessed by digitizing off-air waveforms and calculating and plotting their ambiguity functions [14]. The receiving system was based on a HP8565A spectrum analyzer, digitizing the 21.4 MHz IF output by means of an Echotek ECDR-214-PCI digitizer card mounted in a PC. The system has the advantage of great flexibility, since the centre frequency and bandwidth of the receiver can be set by the controls of the spectrum analyzer. The rather high noise figure of the spectrum analyzer is not a disadvantage, since all of the signals are of high power and propagation is line-of-sight.

Figure 6 shows typical ambiguity functions derived using this system of (a) BBC Radio 4 at 93.5 MHz, for which the programme content is speech (an announcer reading the news), and (b) a digital audio broadcast (DAB) signal at 222.4 MHz. Both show range resolution appropriate to their instantaneous modulation bandwidths (9.1 and 78.6 kHz respectively), though the difference in the sidelobe structure is very evident, showing that the digital modulation format is far superior because the signal is more noise-like.



(a)



(b)

Fig. 6. Typical ambiguity functions: (a) BBC Radio 4 transmission (93.5 MHz) and (b) digital audio broadcast transmission (222.4 MHz).

Table 1 summarizes the measured ambiguity function performance of the various signals captured.

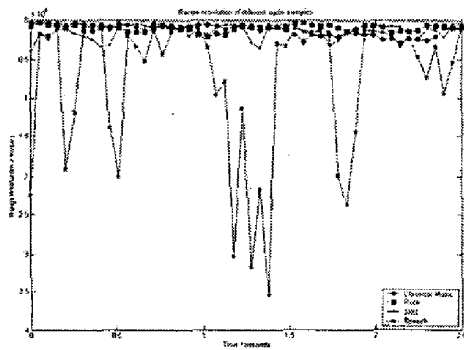


Fig. 7. Variation in range resolution against time for four types of VHF FM radio modulation.

signal	frequency (MHz)	range resolution (km)	effective bandwidth (kHz)	peak range sidelobe level (dB)	peak Doppler sidelobe level (dB)
FM radio: speech (BBC Radio 4)	93.5	16.5	9.1	-19.1	-46.5
FM radio: classical music	100.6	5.8	25.9	-23.9	-32.5
FM radio: rock music (XFM)	104.9	6.55	22.9	-12.0	-26.0
FM radio: reggae (Choice FM)	107.1	1.8	83.5	-27.0	-39.5
DAB	219.4	1.54	97.1	-11.7	-38.0
Analogue TV: chrominance sub-carrier	491.55	9.61	15.6	-0.2	-9.1
Digital TV (DVB-T)	505.0	1.72	87.1	-18.5	-34.6
GSM 900	944.6	1.8	83.3	-9.3	-46.7
GSM 1800	1833.6	2.62	57.2	-6.9	-43.8

Table 1. Properties of ambiguity functions of various types of broadcast and communications signals.

It is also important to know how these properties vary with time, as variations in the form of the ambiguity function will determine the radio system performance. Fig. 7 shows variation in range resolution of four VHF FM radio transmissions, calculated from the  $-3$  dB width of the zero Doppler cut through the ambiguity function, over a 2.5 second interval.

It is evident that for the three types of music the range resolution varies by a factor of two or three, but for the speech modulation the range resolution is badly degraded during pauses between words, by a factor of ten or more.

#### IV. EXAMPLES OF SYSTEMS

##### A. Amateur radio forward scatter experiments

An interesting early example of PCL was given by a radio amateur, the Rev. Dr P.W. Sollom, who had noticed a fluttering effect on VHF amateur signals due to the interference between direct signals and Doppler-shifted echoes from aircraft [24]. The same effect may easily be observed with VHF FM radio and VHF or UHF TV, and works best when the direct signal and scattered signal are of comparable amplitude.

He devised an elegant set of experiments using a VHF TV signal located in northern France as illuminator, and built a two-Yagi interferometer, such that a moving target would pass

through the interferometer grating lobes, allowing the target motion to be estimated from the amplitude modulation.

### B. Non-co-operative radar illuminators

The first work on bistatic radar at University College London was undertaken in the late 1970s. Schoenenberger and Forrest designed and built a system using a UHF Air Traffic Control radar at Heathrow airport as illuminator, and investigated particularly the problems of synchronization between receiver and transmitter [28]. Figure 8 shows a typical PPI display from this system. A real-time co-ordinate correction scheme was also developed for this system.

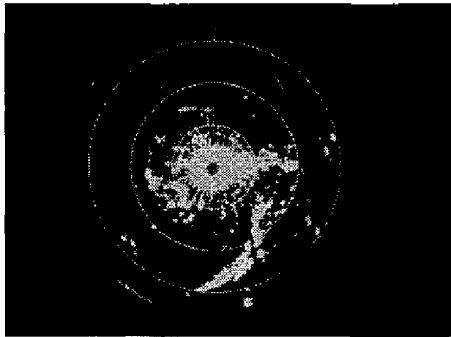


Fig. 8. PPI display from UCL bistatic radar system.

Further developments included a digital beamforming array [9] for pulse chasing experiments (Fig. 9) and a coherent MTI system using clutter from stable local echoes as a phase reference [10].

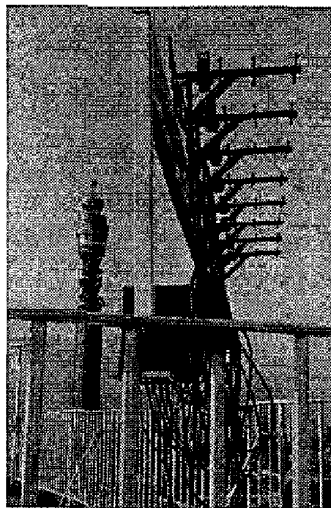


Fig. 9. Digital beamforming array used for pulse chasing experiments with UCL bistatic radar system.

### C. Television-based bistatic radar

Subsequent work at UCL attempted to use UHF television transmissions as illuminators of opportunity, to detect aircraft targets landing and taking off from Heathrow airport, to the west of London [11]. Figure 10 shows the geometry. The results showed that although the television waveforms are very suitable in terms of power and coverage, the analogue television modulation format suffers from ambiguities at the 64  $\mu$ s line repetition rate, which correspond to a bistatic range of 9.6 km.

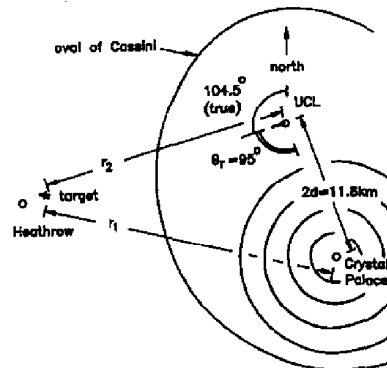


Fig. 10. Horizontal-plane geometry of Crystal Palace television transmitter and Heathrow. Indicated Oval of Cassini is the locus  $r_1 r_2 = 2 \times 10^5$  m.

### D. TV-based forward scatter system

Howland [16] developed a UHF forward scatter system based on television transmissions. Because a forward scatter system is not able to provide range information, he adopted a different approach, measuring angle of arrival (from a two-element interferometer) and Doppler shift of the vision carrier of the television signal. Target tracking was done by an extended Kalman filter algorithm.

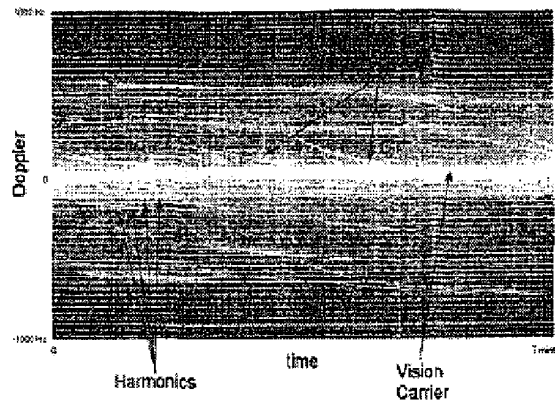


Fig. 11. Example power spectrum against time, around TV vision carrier (after Howland [16]).

He was able to demonstrate tracking of aircraft targets at ranges well in excess of 100 km (Fig. 12).

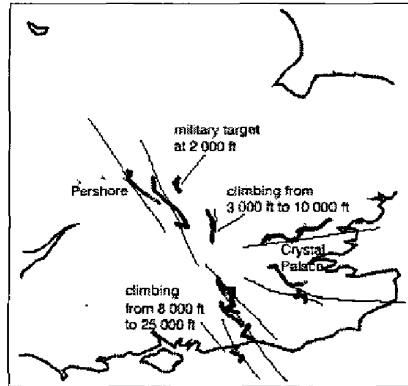


Fig. 12. Track estimates formed on 21 February 1997 between 14:00 and 14:07, compared with secondary radar tracks for the same aircraft (after Howland [16]).

#### E. Silent Sentry

Silent Sentry is a PCL system developed by the Lockheed Martin company, based on multiple VHF FM radio and television transmissions. In its present version (SSIII) it has demonstrated tracking of aircraft and space targets at impressive ranges. It is advertised as being applicable to:

- air surveillance and tracking in areas of limited coverage – a ‘gap filler’;
- capable of tracking low flying, non-cooperative, slow moving targets;
- continuous total volume surveillance of air breathing and ballistic objects;
- low acquisition and operations cost, unattended remotely managed.

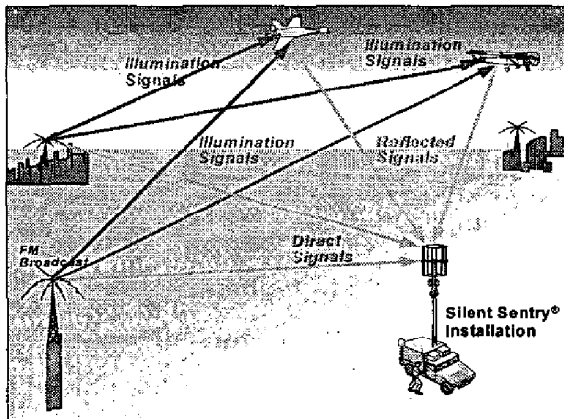


Fig. 13. Principle of operation of Silent Sentry (figure courtesy of Lockheed Martin).

## V. CONCLUSIONS

This paper has attempted to present a review of bistatic radar systems, with particular emphasis on Passive Coherent Location (PCL) techniques. The introduction indicated that the question of whether the present interest is just another peak in the cycle will be addressed. There are several reasons why the answer to this is ‘no’, and that there is reason to believe that practical bistatic radar systems may now be developed and used.

Firstly, there is ever greater spectral congestion. Military operations are likely to be carried out close to centres of population, where there are numerous broadcast and communications signals. For most purposes this spectral congestion is a problem, but for PCL it is a positive advantage. Furthermore, the VHF and UHF frequencies used by high power FM radio and television transmissions are in many senses optimum for PCL.

Secondly, as has already been pointed out, bistatic receivers are potentially simple and cheap.

Thirdly, the advent of GPS solves many of the synchronization and timing problems that have previously limited the performance of bistatic systems.

Fourthly, the inexorable increases in signal processing power mean that many of the signal digitization and processing operations are now feasible in real time. Moore’s law predicts that these advances will continue for many years.

Fertile areas for new work are: (i) the use of phased array antennas and antenna signal processing techniques for ‘pulse chasing’, particularly in the context of multistatic systems, (ii) development of advanced tracking algorithms for multistatic geometries, and (iii) experimental programmes to gather bistatic clutter data, and to develop bistatic clutter models.

## ACKNOWLEDGEMENTS

I acknowledge invaluable discussions with many people from whom I have learned much about bistatic radar over the years. I would particularly like to mention Nick Willis, Paul Howland, John Sahr, DEN Davies, Chris Pell, Chris Baker, and also Ken Milne and Dick Lodwig, both of whom are no longer with us and who are sorely missed. I am grateful to Wendy Underwood and Dennis Freeman of Lockheed Martin, for information on the Silent Sentry PCL system, and I thank my students Hesham Ghaleb, Eero Willman and Rajaram Ramakrishnan for obtaining the results shown in Figure 6 and 7 and Table 1.

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