DOMESTIC SATELLITE COMMUNICATIONS
-The Impact of Recent Advances-

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Cable television embraced communication satellites as a distribution method as early as 1975. In the ensuing years sweeping changes have altered both mediums, and as with most emerging technology based businesses, many of the changes were revolutionary. The ruling, following a body of cable industry research, which allowed use of small aperture (4.5m) receive antennas is an example of one such revolutionary change.

Today both cable TV and satellite communication are mature industries, and as is characteristic of mature industries, what changes do occur are usually of the more subtle evolutionary nature.

Developments of the last year however, have belied that reasoning, and a considerable degree of radical alteration of our delivery medium is again in the offing.

Consider for example that higher power and solid state transponders are already on orbit.

Several encryption schemes have been developed, some or all of which will be deployed on cable oriented services.

New modulation formats such as multiplexed analogue component (MAC) or video FDMA are under serious consideration by programmers, and satellite delivery is the medium which will no doubt be first to convey extended or high definition television.

Interleaved with these developments comes the use at 'C' band of very small aperture, very low cost receive systems designed to operate at carrier to noise levels reduced well beyond those considered feasable as recently as one year ago.

This paper will review these developments from an observers perspective and attempt some objective evaluations of their performance from a largely imperical point of view.

BACKGROUND

More than any single factor, the landmark decision to routinely license small (<9m) receive antennas was responsible for the exponential growth of CATV.

At that juncture the now well known (32-25 log ϕ) expression for antenna sidelobe performance predicated antenna apertures as small as 4.5 meters yielding sufficient off axis discrimination. This, of course, assumed a 4 degree adjacent transmitter environment.

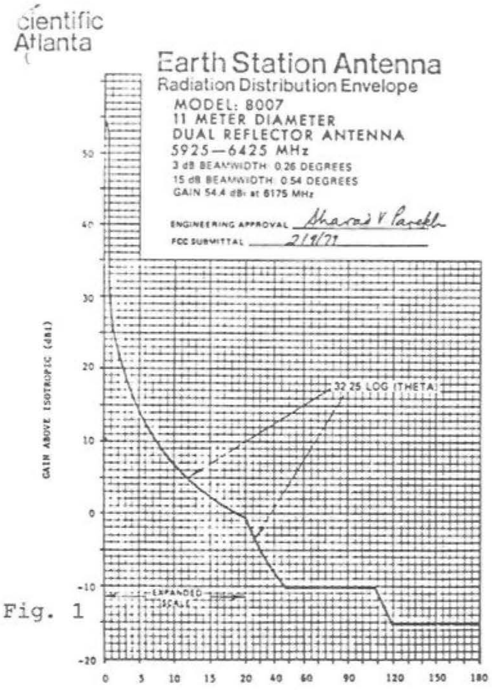

Fig. 1

That same popular acceptance of CATV via satellite was however enjoyed by many other communicators. This resulted in an extraordinary demand for transponders. The supply of which was limited, largely by the 4 degree adjacency rule.

The commission responded by approving a plan of reduced satellite spacing (2 degrees) in 1983. To facilitate such density the performance expectation for receive antennas, was altered accordingly. A more stringent (29-25 log ϕ) envelope was mandated along with other operating practices and a compromised but workable situation anticipated.

One factor expected to complicate matters is the new generation of communication satellites likely to constitute the reduced spacing constellation. Significantly more powerful transmitters than their extant neighbors, the potential for interference they represent is considerable.

Space craft such as advanced Satcom or Galaxy are flying with 8 to 9 watt power amplifiers. The former (Satcom) employing the first of a new generation of solid state output devices. A departure from conventional traveling wave tubes the considerable advantages of S.S.P.A.'s* will be discussed later in this paper.

While higher power adjacencies would be expected to result in a move toward conservative station design utilizing larger aperture more discriminate antennas, current trends are quite the contrary.

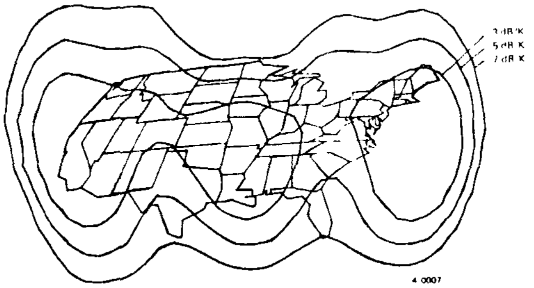

Figure 2 Measured G/T Contours - Satcom IIR

Rather than concern over higher power outputs, users are tending toward exploitation of those EIRP values, which now approach 40dBw. Through lower noise front ends, as well as manipulation of IF bandwidth and aural carriage, antenna apertures have been tested, albeit with varying degrees of success, down to 1.3 meters, at 'C' band.

If such experiments prove successful 'C' band Earth stations could be reduced in cost to a few hundred dollars and installed virtually anywhere.

EVALUATION

Considerable study and information dissemination has accompanied the commissions alteration of the space and Earth segments of the domestic network. The (29-25 log ϕ) specification was the product of much deliberation.

Whether or not to employ very small aperture (<3m) devices will be a free enterprise decision however, and to date little or no definitive data has been forthcoming. No similar restraint has contained the appearance of hardware. Since none of these devices meet anything approaching (29-25 log ϕ), tacit disapproval must be assumed from the commissions refusal to protect them by license.

At this juncture then a closer examination of performance expected from such systems under such conditions is appropriate.

As a starting point reference let's assume a 1.8 meter antenna of 60% efficiency.

The analysis will be for five geo-stationary satellites 2 degrees apart, the satellite of interest being of the advanced class, (8.5 Watts).

The parameters of interest will be limited to those of carrier to noise (c/n) performance and interference immunity (c/i).

The method used is an abreviation of that developed by Golin & Kolsun[1] in 1976, which is considered the definitive analysis.

In the interest of brevity all angles are geocentric.

C/N THERMAL

Conventional TVRO systems for CATV video reception utilize full transponder (36 MHz) bandwidth. Carrier to noise as the aggregate product of uplink and downlink propagation is:

$$C/N = \psi + Ai + G/Tsat - K - 10 \log B$$

Where:

ψ=Saturation flux density for satellite

G/T sat=Figure of merit for satellite.

Ai =Area of isotropic reference antenna

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*Solid State Power Amplifiers

Then:

UPLINK C/N:

$C/N_u = -82+(-37)+(-3dB/K)+(-228.6) - 75.6$
$= 31dB$

DOWNLINK C/N:

$C/N_d = EIRP + G/T - L_p - K - B$

$= 36+(15.33)-196-(-228.6)-75.6$
$= 8.32dB$

UPLINK C/I:

$$C/I_u = EIRP(es) = -\sum_{i=1}^{4} [EIRP_i - G_i + G(i) + P_i]$$

Where:

EIRP(es)=EIRP of wanted transmitter=83dBW

EIRP(i)(1)=EIRP of 1st unwanted E.S.=83dBW

(2)=EIRP of 1st unwanted E.S.=83dBW

(3)=EIRP of 1st unwanted E.S.=83dBW

(4)=EIRP of 1st unwanted E.S.=83dBW

Gi(1)=Tx gain (on axis) of 1st, unwanted antenna = 54 dBi

(2)=Tx gain (on axis) of 2nd unwanted antenna = 54 dBi

(3)=Tx gain (on axis) of 3rd unwanted antenna = 54 dBi

(4)=Tx gain (on axis) of 4th unwanted antenna = 54 dBi

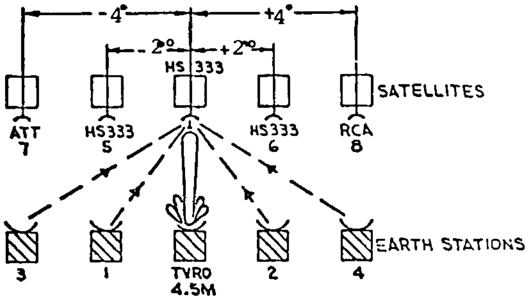
i(1)=Tx gain (2° off axis) of 1st, unwanted antenna = 22dBi

(2)=Tx gain (2° off axis) of 2nd, unwanted antenna = 22dBi

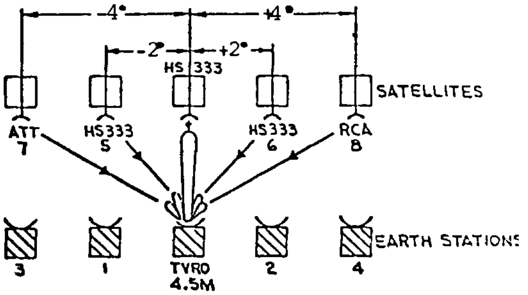
(3)=Tx gain (4° off axis) of 3rd, unwanted antenna = 16dBi

(4)=Tx gain (4° off axis) of 4th, unwanted antenna = 16dBi

Pi = Polarization discrimination for i satellite system. Earth station antennas offer approximately 6dB of off axis polarization discrimination.



UPLINK INTERFERENCE



DOWNLINK INTERFERENCE

Figure 3

Then:

$C/I_u = 83 - [(83-54+29-25\log 2-6)]$
$*(+)[(83-54+29-25\log 2-6)]$
$(+)[(83-54+29-25\log 4-6)]$
$(+)[(83-54+29-25\log 4-6)]$
$= 83 - 48.2$

$C/I_u = 34.8dB$

*Indicates Power Summation

At this point, a serious departure from definitive analysis takes place. The parameter of downlink carrier to interference (C/Id) appears incalcuable. Therefore, all interference calculations have been verified by actual field tests.

Tests were conducted by Warner Amex utilizing a system identical to that described here. Findings failed to produce the expected results. Under all conditions, including no carrier of interest, no evidence of descernable adjacent satellite interference was observed.

Typically a six foot (1.3m) antenna exhibits a three degree (3°) beamwidth. At 2° off axis, the point of most likely interference, the best available 1.3 meter antenna offers no more than 6dB of discrimination.

Using that number and abandoning $(32-25\log\phi)$ the downlink C/Id calculates as follows:

<u>C/Id</u>=

$$
\begin{aligned}
&EIRP(sat)+G(es)-\Sigma[EIRP(sat/i)+Ges(i)+Pi]\\
&\quad =36+35.5-[36+(30-6)]\\
&\quad (+)[36+(30-6)]\\
&\quad (+)[34+(28-6)]\\
&\quad (+)[36+(30-6)]\\
&\quad =71.5-64.9
\end{aligned}
$$

$$C/Id = 6.6dB$$

Despite that 6.6dB appears an abhorently low margin, considering this number against that of $C/Nd=+8.3dB$ the interference energy would be sufficiently below the already marginal carrier level to be indiscernible in the noise. This was supported by the field test results.

Ignoring interference contributions from cross transponder causes and the unknown effects of terrestrial ingress the effective carrier to noise ratio becomes:

$$
\begin{aligned}
C/N\ (eff)&=C/Nu(+)C/Nd(+)C/Iu(+)C/Id\\
&=4.35dB
\end{aligned}
$$

4.35dB is clearly an unacceptable level of performance. This is, of course a worst case scenario and several improvements can be introduced. It does However serve to indicate the inadequacy of the fundamental system.

OPTIMIZATION

As stated several improvements, however subjective, may be imparted, and, since the only application thus far considered for very small aperture stations has been direct reception, no margin for distribution (as via cable) need be considered.

Reduction of I.F. bandwidth can provide significant C/N improvement.

A reduction to 18 MHz (from 36 MHz) provides an improvement to C/N performance of +3dB.

This is a considerable improvement but does impose a penalty. In order to so drastically reduce IFBW, modulation deviation of the carrier must be reduced accordingly. Signal to noise FM improvement reduction results in a random noise performance penalty of approximately 3dB

<u>or</u>:

$$
\begin{aligned}
S/N\ p/p=&C/N(eff)+(20\log\Delta FV/Fvm)+\\
&(10\log B/Fvm)+10\log 6+ew
\end{aligned}
$$

<u>Where</u>:

ΔFv=video deviation
Fvm=Max modulating frequency
ew =weighting & pre emph advantage

Thus, reducing the parameters of ΔFv, & B imposes a corresponding decrease in signal to random noise ratio through loss of FM improvement. An increase in carrier to noise (C/N) of 3dB however reduces the $\Delta S/N$ to only -3dB.

<u>Thus</u>:

$$
\begin{aligned}
S/N\ =&7.35 + 20\log(7/4.2)+ 10\log\\
&(18/4.2)+7.78+13\\
=&38.9dB
\end{aligned}
$$

Removal of subcarrier, and component processing such as MAC, can contribute an additional 3dB of subjective improvemnt to the picture raising the S/N to ≃42dB

Therefore provided an alternate means of aural carriage is available as with most scrambling systems and provided no additional distribution is anticipated and the user is able to reduce deviations and/or IF bandwidth, a 1.8 meter very low cost Earth terminal is capable of yielding passable performance.

Reduction in aperture below 1.8 meters (G/T ≈15dB/°K) however exhibited rapid and pronounced degradations, even under optimum conditions.

High levels of impulse noise were apparent and pointing accuracy proved too precise to be practical.

VIDEO FDMA

Since its inception, conventional domestic satellite video service has been characterized by full transponder (36 MHz) bandwidth.

Despite the robust performance such allocation provides, it quickly exhausts the finite transponder resource.

Until very recently, the demand for transponders on certain satellites far exceeded the supply. In addition the cost of full transponder allocation is often such an inordinate proportion of a programmers operating expense as to prove prohibitive.

Consequently, efforts to imporve video throughput are frequently launched. To date, successful programs have been undertaken by Comsat Corp. & RCA, wherein two (2) and four (4) channels of video respectively are routinely delivered within the bandwidth constraints of a single (36 MHz) transponder,with program audio relegated to a separate delivery source.

The limitation faced by such users however, has been the inability to reach any but the most sensitive Earth stations. This being due primarily to the well known shortcomings of traveling wave tube amplifiers, flown aboard conventional communications satellites, in the presence of multiple carriers. (Abbott, Beakly, Rowse)[2]

A brief review of FDMA deficiencies is in order before proceeding.

REVIEW

Conventional satellite modulation, optimized for video transmission, is distributed across the 36 MHz of available transponder bandwidth as follows:

$$\Delta F=[\Delta fv+(\Delta fe)^2+\Sigma(\chi/fsl\cdot fsi)^2]^{1/2}$$

fv=Deviation of main carrier by video
fe=Deviation of main carrier by E.D.U
χ=Deviation of main carrier by aural Subcarrier
fsi=Frequency of aural subcarrier.
fsn=Frequency of additional aural subcarrier

For the single subcarrier case composite deviations are equal to:

$$[(10.75^2+1^2)+(2/6.8\cdot 6.8)^2]^{1/2}=10.98$$

<u>Then</u>: Δf=10.98MHz
fm=6.8MHz+237KHz

BW=[2(10.95)+2(7.037)]=36.03MHz

LIMITATIONS

Even in the most cursory consideration of a two (FM) carrier per unit bandwidth scheme, the designer will assume deminished performance for a number of expected reasons. The most apparent, of course, being degraded signal to noise performance due to reduced carrier deviations necessary to accommodate bandwidth restrictions, more simply stated:

$$BW=(2\Delta F)+(2FM)$$

Where:

ΔF=Peak composite deviation
FM=Maximum instantaneous modulating frequency.

Results of earlier testing by RCA laboratories verified limitations to 2:1 video transmission to extend well beyond those of power sharing and reduced FM improvement function. The most pronounced of these unfortunately being satellite borne and clearly outside the control fo 2 for 1 aspirants.

For example, conventional satellite transponders utilize high frequency, large output travelling wave tubes as power amplifiers[3]. If nominal EIRP levels are to be expected satellite TWT/P.A.'s must be operated at the region of "saturation". Saturation is characterized by a non-linear input/output power relationship or; as the input power is raised beyond low level (fig. 4) the output power increased in direct proportion, then non-linearly unitil a point is reached where the output will decrease with any additional input.

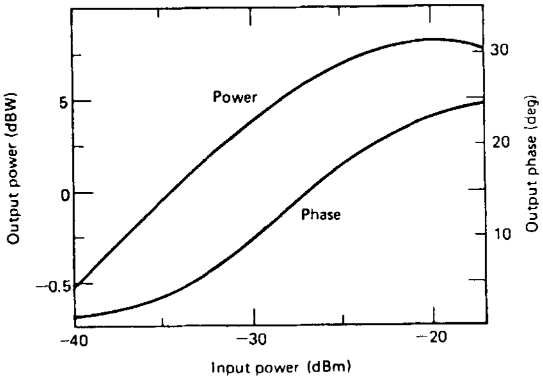


Figure 4 INTELSAT IV single-carrier TWT curves.

Departure from linear operation is manifest as an AM/PM conversion which generally follows input envelope fluxation, and AM/AM conversion hearing a non linear relationship to input flux.

In single carrier operation, considering direct FM modulation, input amplitude levels are constant thus introducing no substantial erroneous output effects.

In the case of multiple carriers, however, a number of degrading effects occur:

1. Non-linearities cause intermodulation products which may fall back into the passband and interfere with one or the other signals and cause disproportionate power sharing.

2. Since two carriers, displaced in frequency are contained within the T.W.T., large excursions of the amplitute envelope will occur. This will translate to phase modulation of the output (AM/PM) resulting in crossmod visible in both reproduced video channels.

In order to minimize these effects operation must be limited to the linear portion of the T.W.T. characteristic curve. The dual carrier power transfer curve developed by RCA experimentation, is considerably reduced over that of single carrier operation.

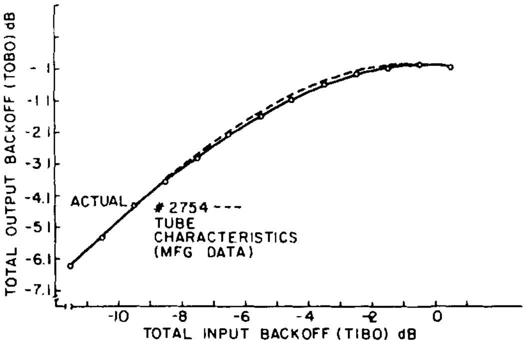


Fig. 5—Single carrier backoff characteristics.

In actual practice input back-off levels are held at approximately -8dB from saturation. This results in a proportionate reduction in satellite EIRP and consequent carrier to noise performance.

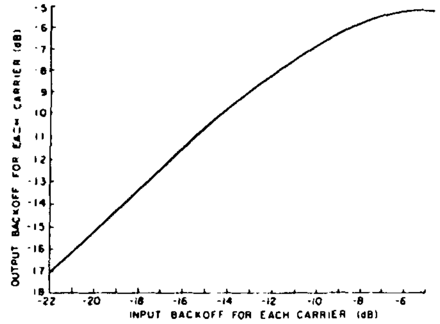


Fig. 6—Two-carrier input versus output backoff relative to single-carrier saturation Carriers at ±9 5 MHz from transponder center (composite from 8/25/76 and 9/1/76, includes HPA)

Reduction in FM improvement ratios, imposed by the narrow (17 MHz) IFBW necessary to accommodate two channels in 36 MHz, dictated operation be limited to Earth stations of typically 33 dB/°K G/T. Or at least 13 meters aperture. Such systems clearly hold no potential for cable reception and have found application primarily in thin route traffic.

EXPERIMENTS WITH ADVANCED SATCOM

In August, 1983 following the launch of RCA's first advanced Satcom satellite a joint experiment was carried out. Engineers from Scientific Atlanta and Warner Amex Satellite Entertainment Company, with the cooperation and assistance of RCA American Communications, undertook to distribute 2:1 video through a single transponder aboard this satellite.

This series of tests differed from previous efforts in three significant areas:

1. This would be the first attempt at video FDMA through a satellite utilizing solid state (non-TWT) power amplifiers, hence referred to as S.S.P.A.'s.

2. Four channels of 15KHz program audio would accompany its associated video within the transponder.

3. Reception would be by a cable grade, seven meter Earth station of 28 dB/°K, G/T.

In order to determine feasibility an ideal system is assumed. Performance assumptions to be verified in practice are as follows:

Video (S/N) Objective =50dB
Channel BW =20 MHz
Guard Band =1 MHz
Satellite EIRP=(Gant+Log^{-1}8.5w/10)=37dBw

Thus to maintain BW=19 MHz, a corresponding reduction in FM deviation equals:

BW=2Δf + 2FM
or:
2fm=8.4 - 19 = 10.6 MHz

Then:ΔF = 5.3 MHz

Using this figure (5.3MHz) to determine receiver transfer function will allow us to determine the necessary C/N ratio which will yield 50 dB S/N as follows:

50=C/N+RTF
=C/N+[20log(Δf/Fvm)+10log(BW/FM)+W]

Where:
ΔF=FM deviation
FVM=Top modulating Frequency
W =Weighting & pre-emph advantage

Then:
50=C/N+[20log(5.3/4.2)+10log(19/4.2)+20.8]

And
50dB=C/N+29.41

Thus: C/N must equal at least <u>20.58dB</u>

We can now determine the minumum Earth station figure of merit which will yield such performance to hals transponder video modulation:

G/T(min)=C/N-EIRP+Lp+K+BW

<u>Where</u>: 1
Lp=Path Loss at 4GHz
K=Boltzmans Constant

<u>Then</u>: 20.58-37+196+(-228.6)+75.6
<u>Thus</u>: G/T(min)=26.5dB/K

Substituting system parameters and solving for G/T will yield actual equipment configurations necessary to meet our performance objectives:

G/T=G(a)-10 log T(sys)

Where:
G(a)= Antenna gain 7 meter
T(sys)= System noise temperature 90K LNA

Then:
G/T = 26.2dB/°K

This is sufficently close to our ideal figure of merit (26.5). That we may then assume a system so configured will yield our performance objectives of S/N=50dB

TEST RESULTS

Results of field tests utilizing a seven meter, 90°K/LNA receive Earth station exceeded predicitons.

Contrary to expectations, the superior linearity of the SSPA aboard Satcom V allowed operation very near saturation. Thus no degradation for input back off was experienced.

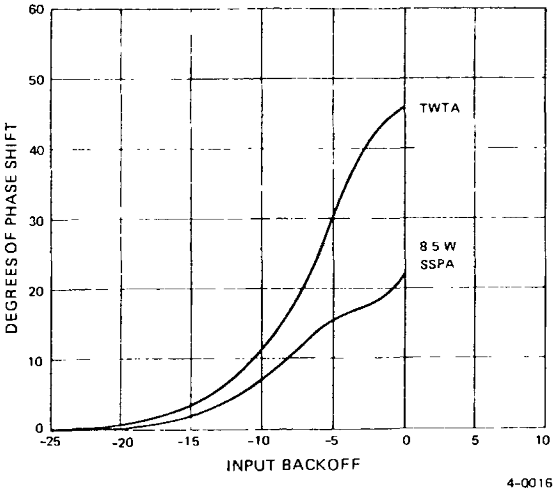


Figure 7 . Phase Shift as a Function of Drive - SSPA vs. TWTA

Power sharing, not included in the previous calculations contributed 3 dB of C/N reduction.

Various configurations yielded the following nominal parameters at Warner-Amex, Long Island, NY facility:

Sat EIRP	37dBW
Antenna S/A	7 meter

LNA Avantek	90K
Exciters S/A 461	18MHz
Frequency Offset	9MHz
High Power Amp's., Varian	3.3KW
Nominal IFBW	17 MHz
IF Filters, Cherychev Slope	17.5MHz
Subcarriers 5.8, 6.2 MHz	-19dB/2MHz

In practice, it was found that video deviations could be increased to 7.5 MHz without discernable overdeviation.

Interference was observed on color bar signals as black dots into lower half of transponder and white dots into upper signal band.

Reduction of subcarrier injection leves from -17 to -19dB, and phase locking of syncronizing pulse generators alleviated all discernable interference.

CONCLUSIONS

Routine operation of 2:1 video can be acheived from advanced Satcom series and presumably future SSPA equipped satellites into what may be described as cable grade earth stations.

The affornentioned experiments yielded:

S/N = 47.5dB, CCIR weighted.

Notably these signals were accompanied by four (4) robust audio channels of:

15KHz, S/N = 60dB.

It is assumed that video baseband processing would yield additional subjective improvements raising S/N ratios above 50 dB.

Acknowledgements:

[1] Jack Golin, Michael Kolcun
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I.T.T. Space Communications, 30 July 1976

[2] L. Abbott, G.W. Beakley, W.T. Rowse
Parameter Trade Offs For Transmitting Two
Television Channels Per Transponder
R.C.A. Review, September 1980

[3] V.K. Bhargava, D. Haccoun, R. Matyus, P. Nuspl
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