Title: From the LHC to the Multiverse

Date: Sep 03, 2008 04:00 PM

URL: http://pirsa.org/08090047

Abstract:

LHC AND THE MULTIVERSE?

Gordy Kane

Perimeter, Sept 08

LHC AND THE MULTIVERSE?

Gordy Kane

Perimeter, Sept 08

Begin with another anthropic coincidence:

We live in a string vacuum

(because string theory addresses all the basic issues)

Without TeV scale data it would become essentially impossible to gain an understanding of our string vacuum – this scale emerges from compactification and supersymmetry breaking, etc. – so the data tells us about those, and how the ground state emerges

At the limit of technology, and the limit of cost, and the limit of society's tolerance for funding acquisition of knowledge, we are barely able to study the TeV scale -- And the laws of electromagnetism allow it!

So, remarkably, we live in a universe where we can describe and understand our string vacuum!

What do we want to understand about our string vacuum?

- What stabilizes the hierarchy between the weak and Planck scales?
- Why our forces [SU(3)xSU(2)xU(1)] and our fundamental particles?
- How is the electroweak symmetry broken?
- Supersymmetry? How is it broken?
- ***Why is the Z mass so small?***
- How do the fermion masses and their hierarchy originate?
- $m_u < m_d$ but $m_t > m_b$?
- Why are neutrino masses very small?
- Why three families?
- Why little or no strong CP violation?
- Why is the universe essentially entirely matter?
- What is the dark matter?
- What is the inflaton?
- Why gauge coupling unification? Forces have common origin?

These are what need explaining

Three things have led some particle theorists to take seriously the idea of the multiverse

- Many solutions of string theory
- Eternal inflation
- No explanation yet of why the cosmological constant is small, or its value

What does the landscape or the multiverse have to do with learning about our string vacuum, and what we want to understand?

Two related perspectives:

- Seems to be "orthogonal" – IIB flux vacua, counting, do not seem to affect any understanding of the issues above – seems to be many equivalent vacua *with any given set of phenomenological properties*

- In constructing any particular vacuum, do not expect to get a small CC – Calculate a scalar potential, and must tune its value at the minimum to be small – may be crucial to do so -- can only do that tuning if have enough essentially equivalent vacua – Doing that seems to give testable predictions about LHC signatures, dark matter, etc!

Most of rest of talk – pursue the 2nd point:

- Take as an example our M theory compactification on a G2 manifold and illustrate how the tuning may work, and how it implies predictions – and how it addresses most of what we would like to understand about our vacuum
- Discuss a little how much we can hope to calculate about any particular string vacuum?

  -- everything?

  -- nothing – i.e. can we find ours

  -- everything but CC? – argumentem ad antiquitatem [for our purposes, if you haven't been able to calculate something so far, you will never be able to calculate it]?
- Briefly discuss superposition of vacua to explain why CC is not large – Bloch spectrum – relax to lowest state – gives a different inflation approach, predictive

Compactify M theory on 7D manifold with G_2 holonomy

-- break susy, stabilize moduli and *generate* TeV scale

-- LHC and dark matter and moduli phenomenology, etc

Bobby Acharya, Konstantin Bobkov, Kane, Piyush Kumar, Diana Vaman, hep-th/0606262

Acharya, Bobkov, Kane, Kumar, Jing Shao,

hep-ph/0701034 – susy, moduli stabilization, minimize scalar potential, $M_{3/2}$~TeV, gaugino masses suppressed

0801.0478 – spectrum, dark matter, moduli masses, LHC, gauge coupling unification

0804.0863 – DM relic density, no moduli and gravitino problems

Currently under study – LHC signatures, embedding SM matter rigorously, CPV, baryogenesis, inflation

Earlier work on M theory/G_2

-- results relevant for realistic matter physics such as existence of non-abelian gauge fields and chiral fermions; general form of Kahler potential; issues related to local constructions (e.g. SU(5)→SM) such as proton decay, threshold corrections to gauge couplings, Yukawas.

- Atiyah and Witten, th/0107177
- Acharya and Witten, th/0109152
- Witten, ph/0201018
- Beasley and Witten, th/0203061
- Friedmann and Witten, th/0211269
- Acharya and Valandro, ph/0512144
- Acharya and Gukov, th/0409101
- Lukas, de Carlos et al, th/0606286; th/0411071; th/0409256

Don't explicitly discuss these here

Pirsa: 08090047

Compactify M theory on 7D manifold with G_2 holonomy

-- break susy, stabilize moduli and *generate* TeV scale

-- LHC and dark matter and moduli phenomenology, etc

Bobby Acharya, Konstantin Bobkov, Kane, Piyush Kumar, Diana Vaman, hep-th/0606262

Acharya, Bobkov, Kane, Kumar, Jing Shao,

hep-ph/0701034 – susy, moduli stabilization, minimize scalar potential, $M_{3/2}$~TeV, gaugino masses suppressed

0801.0478 – spectrum, dark matter, moduli masses, LHC, gauge coupling unification

0804.0863 – DM relic density, no moduli and gravitino problems

Currently under study – LHC signatures, embedding SM matter rigorously, CPV, baryogenesis, inflation

Earlier work on M theory/G_2

-- results relevant for realistic matter physics such as existence of non-abelian gauge fields and chiral fermions; general form of Kahler potential; issues related to local constructions (e.g. SU(5)→SM) such as proton decay, threshold corrections to gauge couplings, Yukawas.

- Atiyah and Witten, th/0107177
- Acharya and Witten, th/0109152
- Witten, ph/0201018
- Beasley and Witten, th/0203061
- Friedmann and Witten, th/0211269
- Acharya and Valandro, ph/0512144
- Acharya and Gukov, th/0409101
- Lukas, de Carlos et al, th/0606286; th/0411071; th/0409256

Don't explicitly discuss these here

Pirsa: 08090047

Our work:

Given a set of (dimensionless) "microscopic" parameters characterizing the vacua, and assumptions about the existence of the G_2 manifold, we simultaneously

-- Generate the EW scale in a unique metastable de Sitter vacuum with spontaneous ~~SUSY~~

-- Stabilize the moduli in fluxless vacua – all moduli that occur in gauge kinetic function, all that affect observables such as gauge couplings, higgs vev, dark matter, LHC, etc

-- Results consistent with standard gauge unification ($M_{unif} \sim 10^{16}$ GeV)

-- Assume a natural GUT visible sector breaking to MSSM chiral spectrum → phenomenological predictions, e.g. for LHC and DM, basically unique

Only dimensionful input – the Planck scale !

Presumably can combine this with earlier work on matter

Earlier work on M theory/G_2

-- results relevant for realistic matter physics such as existence of non-abelian gauge fields and chiral fermions; general form of Kahler potential; issues related to local constructions (e.g. SU(5)→SM) such as proton decay, threshold corrections to gauge couplings, Yukawas.

- Atiyah and Witten, th/0107177
- Acharya and Witten, th/0109152
- Witten, ph/0201018
- Beasley and Witten, th/0203061
- Friedmann and Witten, th/0211269
- Acharya and Valandro, ph/0512144
- Acharya and Gukov, th/0409101
- Lukas, de Carlos et al, th/0606286; th/0411071; th/0409256

Don't explicitly discuss these here

Pirsa: 08090047

Our work:

Given a set of (dimensionless) "microscopic" parameters characterizing the vacua, and assumptions about the existence of the G_2 manifold, we simultaneously

-- Generate the EW scale in a unique metastable de Sitter vacuum with spontaneous ~~SUSY~~

-- Stabilize the moduli in fluxless vacua – all moduli that occur in gauge kinetic function, all that affect observables such as gauge couplings, higgs vev, dark matter, LHC, etc

-- Results consistent with standard gauge unification ($M_{unif} \sim 10^{16}$ GeV)

-- Assume a natural GUT visible sector breaking to MSSM chiral spectrum → phenomenological predictions, e.g. for LHC and DM, basically unique

Only dimensionful input – the Planck scale !

Presumably can combine this with earlier work on matter

STRINGY

- 7 compact dimensions form a space with G_2 holonomy, preserves N=1 supersymmetry in 4D

- No fluxes -- not needed for stabilization in our case, tend to raise masses to string scale

- In these vacua, non-Abelian gauge fields localized along 3D submanifolds at which there is an orbifold singularity [Acharya, th/9812205;th/0011089; Acharya-Gukov th/0409191]

- Chiral fermions localized at points at which there are conical singularities [Acharya and Witten, th/0109152; Acharya and Gukov, th/0409191; Atiyah and Witten, th/0107177]

- Generically two 3D submanifolds do not intersect in a 7D space, so no light matter fields charged under both SM gauge group and hidden sector gauge groups → susy breaking generically gravity mediated in these vacua

A set of Kahler potentials, consistent with G_2 holonomy and known to describe some explicit examples, was given by Beasley-Witten th/0203061; Acharya, Denef, Valandro th/0502060, with

$$K = -3\ln(4\pi^{1/3} V_X)$$

$$V_X = \prod_{i=1}^{N} s_i^{a_i}, \quad \text{with} \quad \sum_{i=1}^{N} a_i = 7/3$$

The a_i are rational numbers.

Assume hidden sector gaugino condensation

$$W = \sum_{k=1}^{M} A_k e^{ib_k f_k}$$

gauge kinetic function

One term enough to stabilize all relevant moduli generically – but we are not guaranteed to be in region where supergravity approximations valid

Keep two terms for analytic treatments, more numerically – enough to find solutions with good properties such as being in supergravity regime, simple enough to do most calculations semi-analytically (as well as numerically) – have checked some results more generally

$b_k = 2\pi/c_k$ where c_k are dual coxeter numbers of hidden sector gauge groups --- A_k are constants of order unity, and depend on threshold corrections to gauge couplings, some computed by Friedmann and Witten

The gauge kinetic functions here are integer linear combinations of all the moduli (Lukas, Morris th/0305078),

$$f_k = \sum_{i=1}^{N} N_i^k z_i .$$

The microscopic constants a_i, b_k, A_k, N_i^k are determined for a given G_2 manifold (but not yet known for relevant ones) --they completely characterize the vacua – these constants not dependent on moduli

Focus analytically on the (well-motivated) case where two hidden sector gauge kinetic functions are equal (the corresponding three-cycles are in the same homology class)

Include massless hidden sector quark states Q with N_c colors, N_f flavors, $N_f<N_c$ -- then (Affleck, Dine, Seiberg PRL 51(1983)1026, Seiberg hep-th/9402044, hep-th/9309335, see also Lebedev,Nilles, Ratz th/0603047)

$$W = A_1 e^{i\frac{2\pi}{N_c-N_f}\sum_{i=1}^{N} N_i^{(1)} z_i} \det(Q\tilde{Q})^{-\frac{1}{N_c-N_f}} = A_1 \phi^a e^{ib_1 f_1}$$

and define an effective meson field

$$\phi \equiv \left(\det(Q\tilde{Q})\right)^{1/2} = \phi_0 e^{i\theta}$$

The N=1 SUGRA scalar potential is then given by:

$$V = \frac{e^{\phi_0^2}}{48\pi V_X^3}\Big[\big(b_1^2A_1^2\phi_0^{2a}e^{-2b_1\vec{\nu}\cdot\vec{a}} + b_2^2A_2^2e^{-2b_2\vec{\nu}\cdot\vec{a}} + 2b_1b_2A_1A_2\phi_0^a e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}}\cos\big((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta\big)\big)$$

$$\times\sum_{i=1}^{N}a_i(\nu_i)^2 + 3(\vec{\nu}\cdot\vec{a})\big(b_1A_1^2\phi_0^{2a}e^{-2b_1\vec{\nu}\cdot\vec{a}} + b_2A_2^2e^{-2b_2\vec{\nu}\cdot\vec{a}} + (b_1+b_2)A_1A_2\phi_0^a e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}}$$

$$\times\cos\big((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta\big)\big) + 3\big(A_1^2\phi_0^{2a}e^{-2b_1\vec{\nu}\cdot\vec{a}} + A_2^2e^{-2b_2\vec{\nu}\cdot\vec{a}} + 2A_1A_2\phi_0^a e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}} \qquad (101)$$

$$\times\cos\big((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta\big)\big) + \frac{3}{4}\phi_0^2\Big(A_1^2\phi_0^{2a}\left(\frac{a}{\phi_0^2}+1\right)^2e^{-2b_1\vec{\nu}\cdot\vec{a}} + A_2^2e^{-2b_2\vec{\nu}\cdot\vec{a}}$$

$$+2A_1A_2\phi_0^a\left(\frac{a}{\phi_0^2}+1\right)e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}}\cos\big((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta\big)\Big)\Big].$$

- Can minimize the above potential analytically in the large hidden sector 3-cycle volume approximation (i.e. volumes >1, supergravity approximation valid). Consistently take higher order effects into account.

- After long analysis, find to lowest order [P,Q ranks of hidden sector gauge groups]

Q-P>2

$$s_i = \frac{a_i \nu}{N_i}, \quad \text{with} \quad \nu \approx \frac{3}{14\pi} \frac{PQ}{Q-P} \log\left(\frac{A_1 Q}{A_2 P}\right)$$

P_{eff}

$$\phi_0^2 \approx 1 - \frac{2}{Q-P} + \sqrt{1 - \frac{2}{Q-P} - \frac{7}{P \log\left(\frac{A_1 Q}{A_2 P}\right)}} \left(\frac{3}{2} + \sqrt{1 - \frac{2}{Q-P}}\right)$$

"unique" for a given set of microscopic parameters.

- leading order condition for energy density at minimum to be positive easy to satisfy →deSitter minimum, metastable

$$3-\frac{8}{Q-P}-\frac{28}{P\log\left(\frac{A_1Q}{A_2P}\right)}<0$$

- equality makes potential vanish at minimum →

$$P\log\left(\frac{A_1Q}{A_2P}\right)=\frac{28(Q-P)}{3(Q-P)-8}$$

Q-P=3

→ $\sim$ 30% of entire parameter space (defined so supergravity valid) has gravitino mass $\lesssim$ 100 TeV – once use condition to give zero at minimum, ***all*** solutions below $\sim$ 100 TeV

→ Gaugino masses suppressed over entire parameter space by stringy factor $P_{eff} \lesssim 84$

Recall – no fluxes, no anti-branes – susy broken spontaneously

- P(SU(N))=N
- P(SO(2N))=2N-2
- P(E6)=18
- P(E8)=30

So need $\log(A_1P/A_2Q) \sim$ 3-8, so A_1P/A_2Q large

-- Depends on threshold corrections at string scale

-- computed by Friedmann and Witten for one Len's space, $SU(3)/Z_q$

-- can do it, but very tuned – need q large

-- Malcolm Perry recently got interested in computation and has carried it out for several Len's spaces – work underway to calculate P_{eff} for those

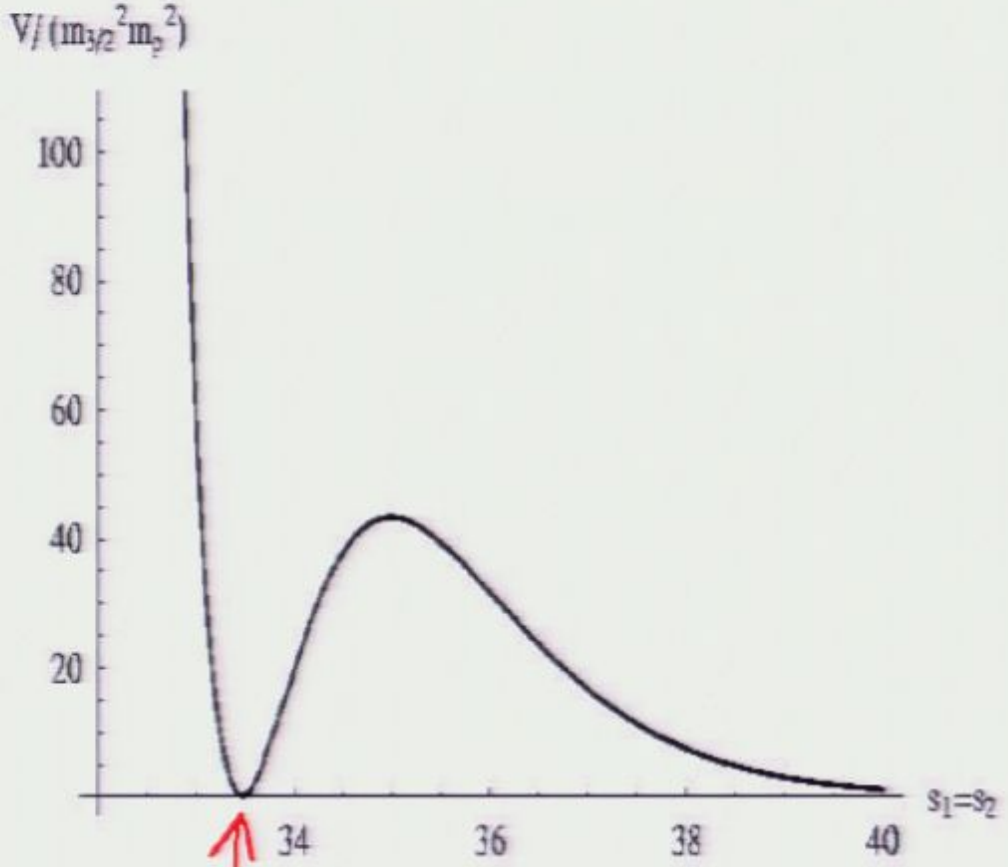


FIG. 9: Potential in units of $m_{3/2}^2 m_p^2$ along the slice $s_1 = s_2$ for a manifold with two moduli with the meson field equal to its value at the minimum of the potential (134). The microscopic constants are as in (136). Although hard to see from the graph, the value of the potential at the minimum (i.e. the cosmological constant) is $0.194\, m_{3/2}^2 m_p^2$.

$(m_{3/2}^2 \; m_{Pl}^2)$

- P(SU(N))=N
- P(SO(2N))=2N-2
- P(E6)=18
- P(E8)=30

So need $\log(A_1P/A_2Q) \sim$ 3-8, so A_1P/A_2Q large

-- Depends on threshold corrections at string scale

-- computed by Friedmann and Witten for one Len's space, $SU(3)/Z_q$

-- can do it, but very tuned – need q large

-- Malcolm Perry recently got interested in computation and has carried it out for several Len's spaces – work underway to calculate P_{eff} for those

Compute GRAVITINO MASS

$$m_{3/2} = m_p \sqrt{2}\pi^3 A_2 \left| \frac{P}{Q} \phi_0^{-\frac{2}{P}} - 1 \right| \left(\frac{28Q}{3(Q-P)-8} \right)^{-\frac{7}{2}} e^{-\frac{28}{3(Q-P)-8}} \prod_{i=1}^{N} \left(\frac{7N_i}{3a_i} \right)^{\frac{3a_i}{2}} e^{\phi_0^2/2}$$

where the meson vev is now given by:

$$\phi_0^2 \approx -\frac{1}{8} + \frac{1}{Q-P} + \frac{1}{4}\sqrt{1-\frac{2}{Q-P}} + \frac{2}{Q-P}\sqrt{1-\frac{2}{Q-P}}.$$

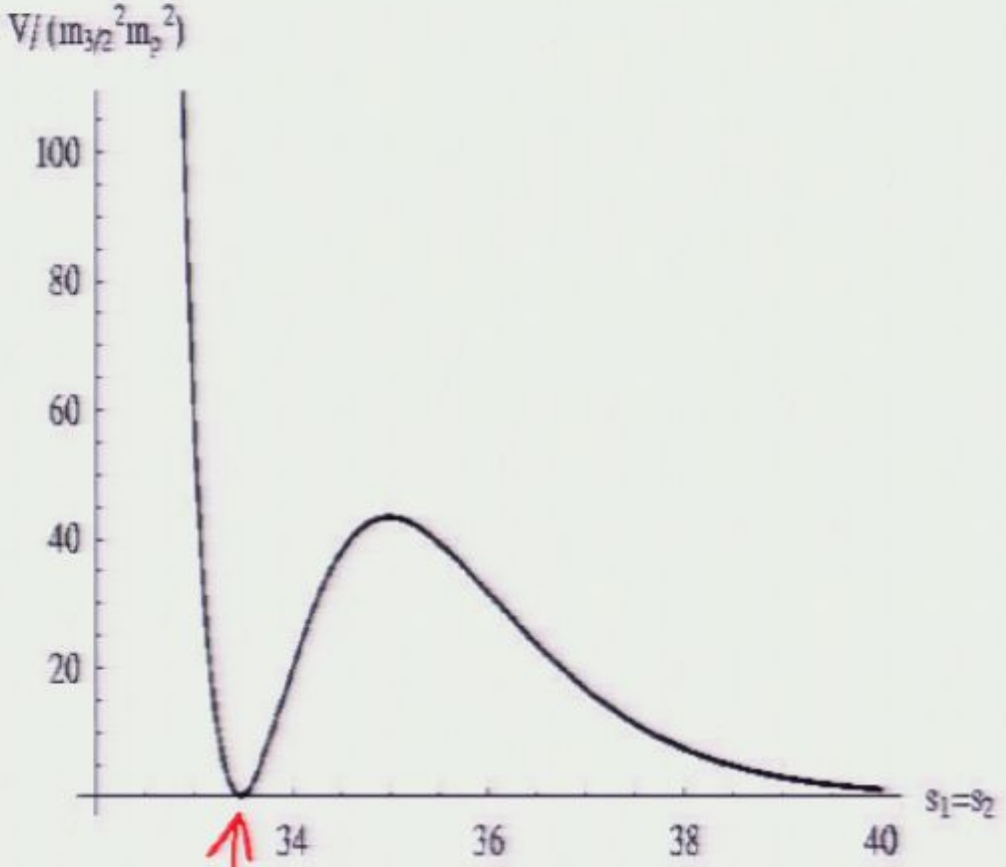


FIG. 9: Potential in units of $m_{3/2}^2 m_p^2$ along the slice $s_1 = s_2$ for a manifold with two moduli with the meson field equal to its value at the minimum of the potential (134). The microscopic constants are as in (136). Although hard to see from the graph, the value of the potential at the minimum (i.e. the cosmological constant) is $0.194\, m_{3/2}^2 m_p^2$.

$(m_{3/2}^2 m_{Pl}^2)$

COSMOLOGICAL CONSTANT?

No solution in G_2 vacuum (or presumably in any particular vacuum)

Can we still do meaningful phenomenology?

Set V_0 (potential at minimum) to zero at leading order by tuning A_1Q/A_2P

We check that tuning V_0 numerically has little effect on $M_{3/2}$ and on superpartner masses and decay branching ratios, dark matter relic density and detectability, etc

COSMOLOGICAL CONSTANT?

No solution in G_2 vacuum (or presumably in any particular vacuum)

Can we still do meaningful phenomenology?

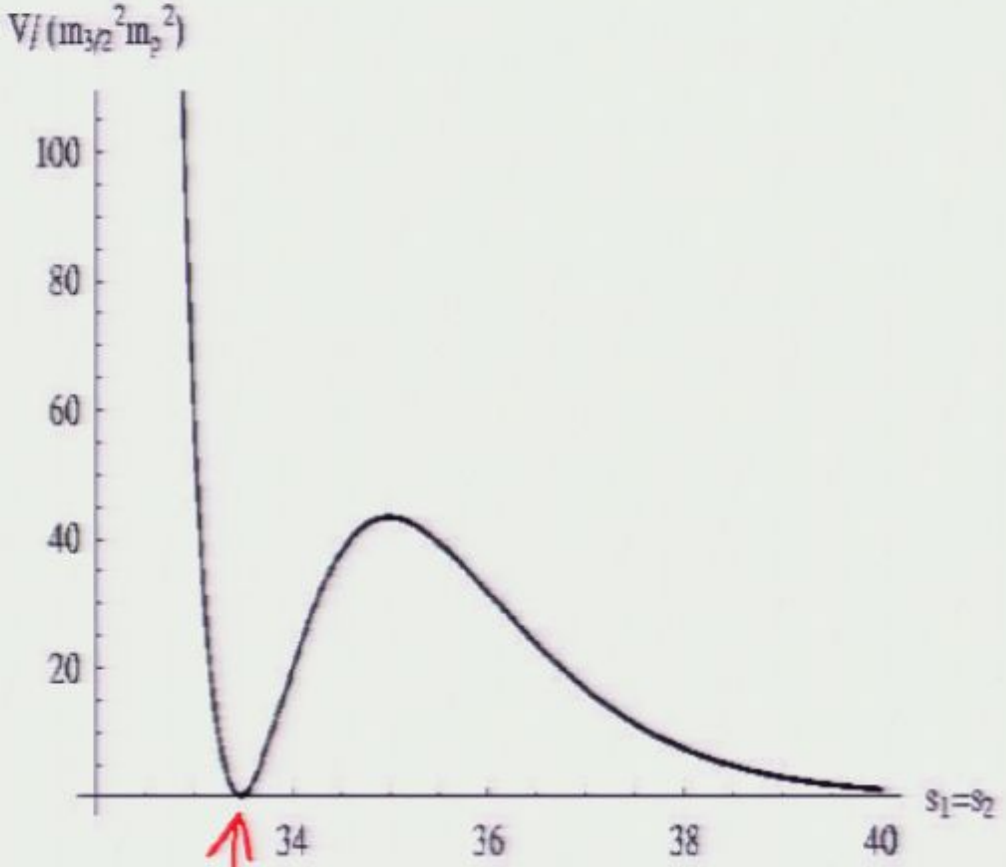


FIG. 9: Potential in units of $m_{3/2}^2 m_p^2$ along the slice $s_1 = s_2$ for a manifold with two moduli with the meson field equal to its value at the minimum of the potential (134). The microscopic constants are as in (136). Although hard to see from the graph, the value of the potential at the minimum (i.e. the cosmological constant) is $0.194\, m_{3/2}^2 m_p^2$.

$(m_{3/2}^2 \; m_{Pl}^2)$

COSMOLOGICAL CONSTANT?

No solution in G_2 vacuum (or presumably in any particular vacuum)

Can we still do meaningful phenomenology?

COSMOLOGICAL CONSTANT?

No solution in G_2 vacuum (or presumably in any particular vacuum)

Can we still do meaningful phenomenology?

Set V_0 (potential at minimum) to zero at leading order by tuning $A_1 Q / A_2 P$

We check that tuning V_0 numerically has little effect on $M_{3/2}$ and on superpartner masses and decay branching ratios, dark matter relic density and detectability, etc

Condition from setting CC to zero at tree level seems to imply a relation between small CC and $M_{3/2} \sim$ TeV

→ do not have to *independently* tune CC to be small *and* $M_{3/2}$ to be $\sim$ TeV !

TREE LEVEL GAUGINO MASSES

- Universal since assume SU(5) or similar unification near string scale
- With same assumptions as used so far, get

$$M \approx -\frac{e^{-i\gamma w}}{P \log\left(\frac{A_1 Q}{A_2 P}\right)}\left(1+\frac{2}{\phi_0^2(Q-P)}+\frac{7}{\phi_0^2 P \log\left(\frac{A_1 Q}{A_2 P}\right)}\right)\times m_{3/2}$$

- Independent of SM or hidden sector gauge kinetic functions and details of internal manifold (a_i) and number of moduli N
- Gaugino masses suppressed by factor that depends (only) on microscopic theory, corrections $\sim$ 1/(volume of 3-cycle)

$$M \approx -\frac{e^{-i\gamma w}}{84}\left(1+\frac{2}{3\phi_0^2}+\frac{7}{84\phi_0^2}\right)\times m_{3/2} \approx -e^{-i\gamma w}\,0.024\times m_{3/2}$$

• Anomaly mediated gaugino masses

Gaillard, Nelson, Wu, hep-th/09905122; Bagger et. al.: hep-th/9911029

$$(M)_a^m = -\frac{g_a^2}{16\pi^2}\left[-\left(3C_a - \sum_\alpha C_a^\alpha\right)e^{\hat{K}/2}W^* + \left(C_a - \sum_\alpha C_a^\alpha\right)e^{\hat{K}/2}F^m K_m + 2\sum_\alpha C_a^\alpha e^{\hat{K}/2}F^m \partial_m \ln \tilde{K}_\alpha\right]$$

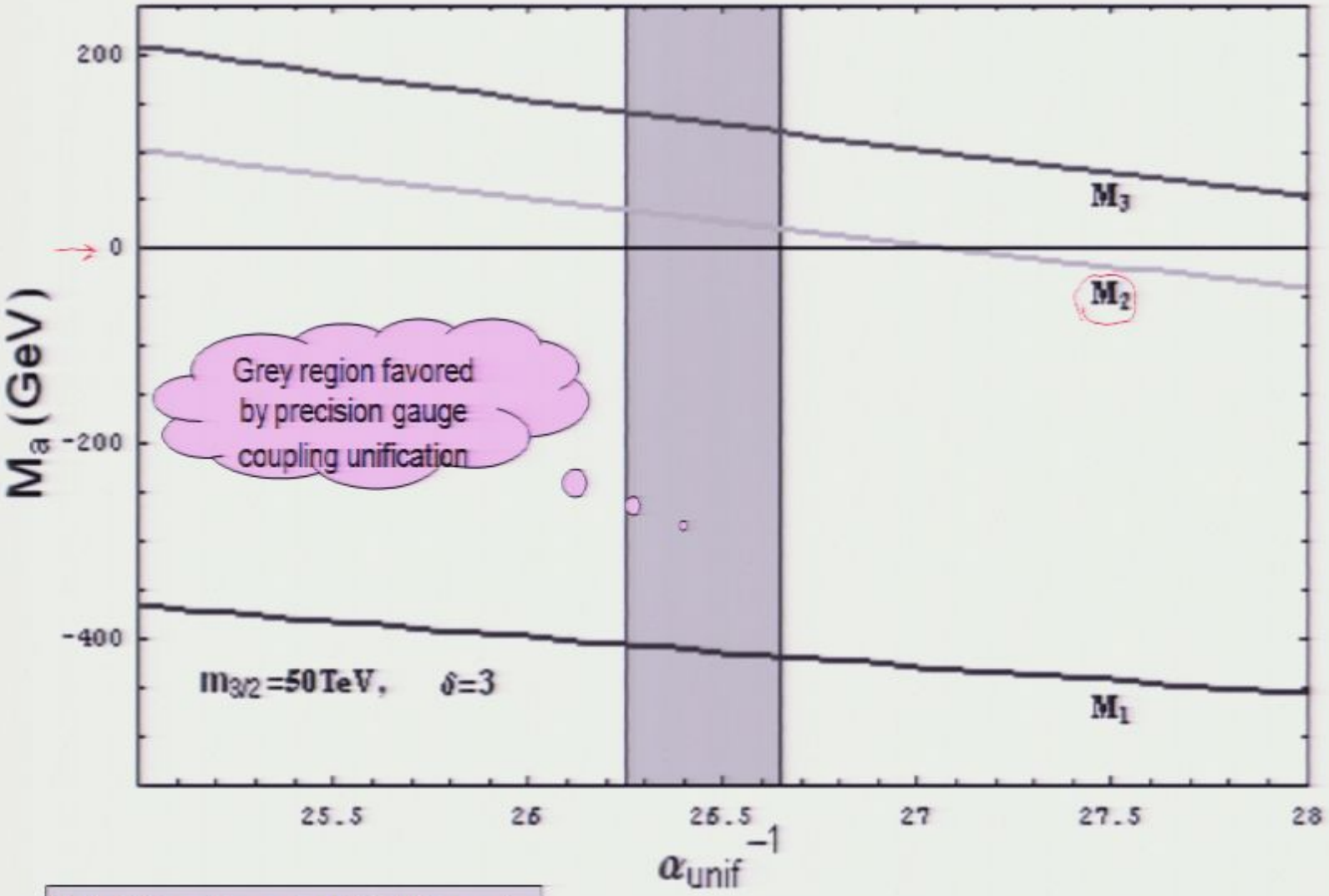
--Note depends on α_{unif} -- potential contributions from KK threshold effects zero here

•Lift the Type IIA Kahler potential (Bertolini et al th/0512067) to M-theory.

$$\tilde{K}_{\bar{\alpha}\beta} = \delta_{\bar{\alpha}\beta}\prod_{i=1}^{n}\left(\frac{\Gamma(1-\theta_i^\alpha)}{\Gamma(\theta_i^\alpha)}\right)^{\frac{1}{2}}, \quad \tan\left(\pi\theta_i^\alpha\right) = c_i^\alpha (s_i)^l$$

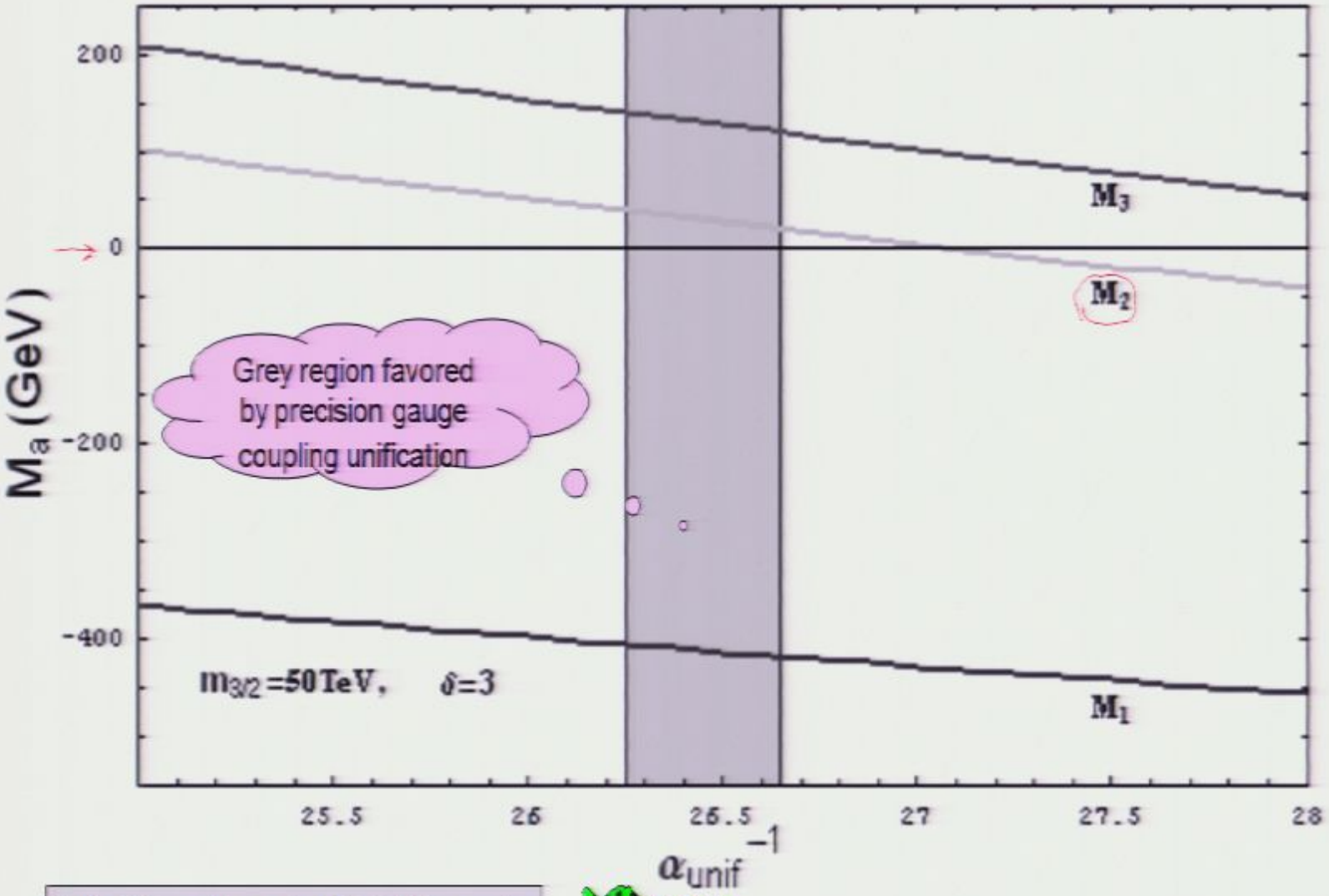
Tree level and anomaly mediated contributions almost same size, so major cancellations, depending on α_{unif} – somewhat surprising

High scale gaugino masses – not universal



Note M2 small so wino LSP, M3 runs to be larger at low scale

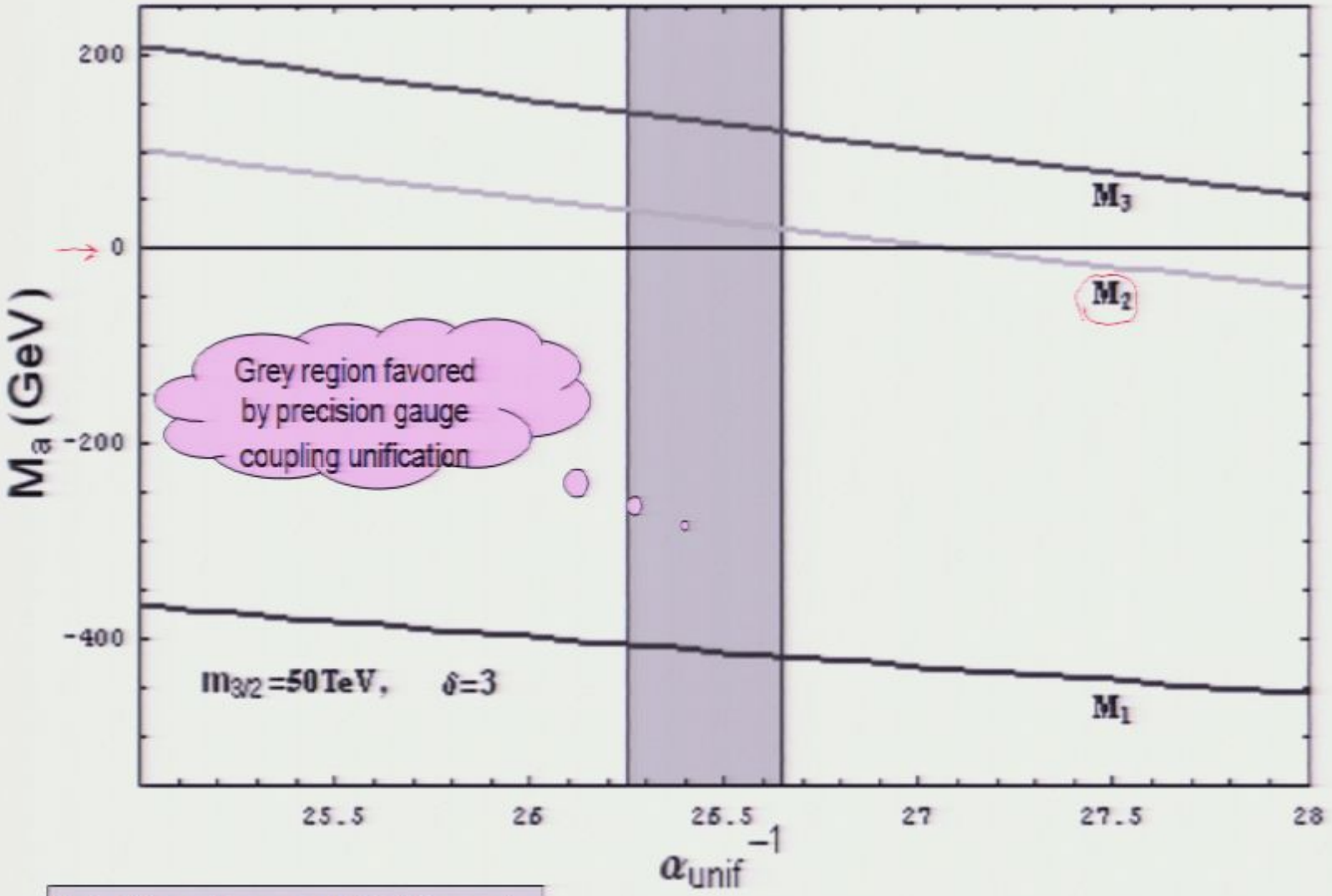
High scale gaugino masses – not universal



Note M2 small so wino LSP, M3 runs to be larger at low scale

Mute

High scale gaugino masses – not universal



Note M2 small so wino LSP, M3 runs to be larger at low scale

High scale scalar masses

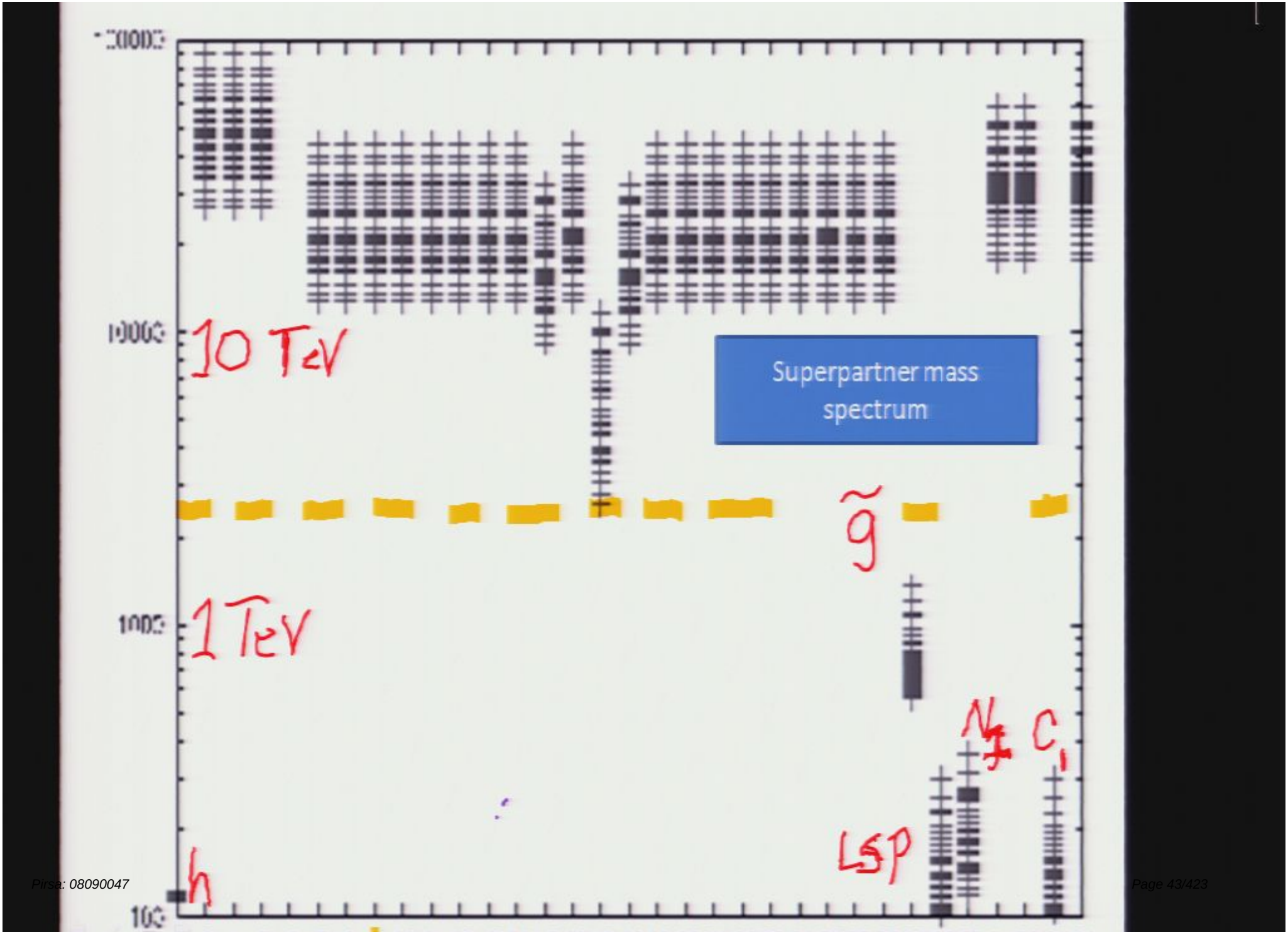
$$m_\alpha^2 \approx \cancel{V_0} + m_{3/2}^2\left[1+\frac{9}{4P^2\ln^2\left(\frac{A_1 Q}{A_2 P}\right)}\left(1+\frac{2}{(Q-P)\phi_0^2}+\frac{7}{\phi_0^2 P\ln\left(\frac{A_1 Q}{A_2 P}\right)}\right)^2\right.$$

$$\left.\times\frac{1}{4\pi}\sum_i\left\{l^2\psi_{ii}^\alpha\sin^2\left(2\pi\theta_i^\alpha\right)+l^2\psi_i^\alpha\sin\left(4\pi\theta_i^\alpha\right)-2l\psi_i^\alpha\sin\left(2\pi\theta_i^\alpha\right)\right\}\right]$$

- If we require zero CC at tree-level and $Q-P=3$:

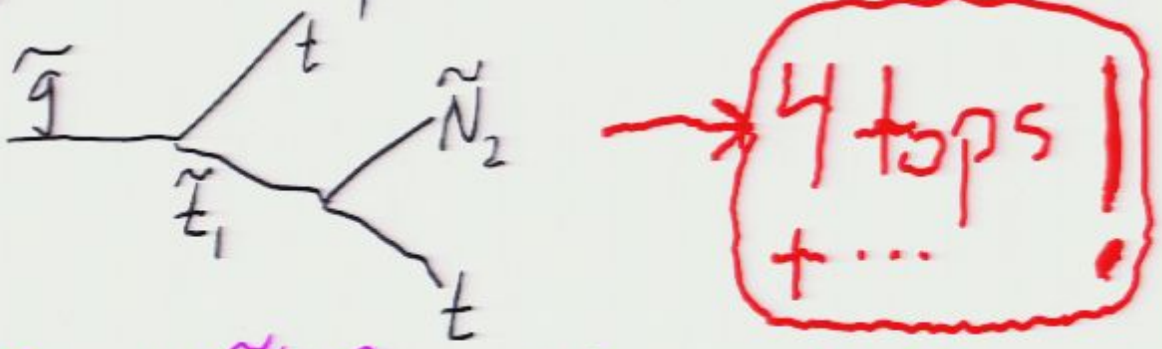
$$m_\alpha^2 \approx m_{3/2}^2\left[1-\frac{0.0013}{4\pi}\sum_i\left\{l^2\psi_{ii}^\alpha\sin^2\left(2\pi\theta_i^\alpha\right)+l^2\psi_i^\alpha\sin\left(4\pi\theta_i^\alpha\right)-2l\psi_i^\alpha\sin\left(2\pi\theta_i^\alpha\right)\right\}\right]$$

→ Universal heavy scalars $m_\alpha \approx m_{3/2}$


10 TeV
1 TeV
Superpartner mass spectrum
$\tilde{g}$
N_1 C_1
LSP
h

- gluinos produced, $\sigma \sim$ few pb
- RGE running from $M_{3/2}$ and scalar scale gives lightest stop significantly lighter than other scalars (few TeV), so it dominates gluino decay

- $\tilde{t}_1 \approx \tilde{t}_R$, $\tilde{N}_1 \approx \tilde{W}^0$, $\tilde{C}_1^{\pm} \approx \tilde{W}_1^{\pm}$
- So $\tilde{N}_1, \tilde{C}_1$ mainly don't couple to $\tilde{t}_1$
- So dominant gluino decay is



- Also some $\tilde{g} \to t b \tilde{C}_1^{\pm}$ from mixing, and $\tilde{g} \to \tilde{N}_2 g \sim \frac{1}{2}\%$
- $\tilde{N}_2 \to W \tilde{C}$
  $\to l\nu, q'\bar{q}$

Assume tuning allowed – naively need $\sim 10^{90}$ vacua with SM forces and quarks and leptons, essentially same superpartner spectra, etc

Actually, if just use criterion that don't want to affect LHC predictions, could use $\sim$ 10 GeV, so $\sim 10^{40}$ -- but maybe many of the others excluded by Weinberg anthropic argument – need to know measure to say that, and can in principle calculate the measure – interesting to work out which predictions, explanations need CC small

But do need multiverse to understand our string vacuum!

Having ***small*** CC (< few GeV) has indirect implications for our string vacuum as well – gaugino masses suppressed, observable – dark matter and its relic density – etc

Actual value of CC, i.e. dark energy, seems not to be important here

Assumed some LHC signal – supersymmetry only interesting one since it can connect the EW, TeV scales with the "Planck" scale

Supersymmetry has an "ultraviolet completion"

- What stabilizes the hierarchy between the weak and Planck scales?
- Supersymmetry? How is it broken?
- Why is M_Z so small
- Why our forces [SU(3)xSU(2)xU(1)] and our fundamental particles?
- How is the electroweak symmetry broken?
- How to the fermion masses and their hierarchy orginate?
- $M_u < m_d$ but $m_t > m_b$?
- Why are neutrino masses very small?
- Why three families?
- Why little or no strong CP violation?
- Why is the universe essentially entirely matter?
- What is the dark matter?
- What is the inflaton?
- Why gauge coupling unification?

Red, plus LEP/Tevatron light Higgs, and no effects BTSM point to supersymmetry

What can we calculate in our string vacuum?

-- measure a few things, calculate some, understand list

-- also calculate CC? small? Value?

Now turn to a phenomenological approach/framework to early universe cosmology, in which quantum fluctuations

- could give a small positive non-anthropic cosmological constant, and
- could give satisfactory inflation without scalar field inflatons

– several major assumptions

– first summarize approach and examine if phenomenologically all right
  – then hope to fill in top-down derivations of assumptions

-- summarize issues and obstacles

-- unconventional

hep-th/0311152 GK, Perry, Zytkow

-- basic idea, coherent wave function of the universe over many vacua, quantum mechanics → Bloch band structure – field theory calculation

hep-th/0407217 GK, Perry Zytkow

-- de Sitter two well tunneling

hep-th/0610054 Adams, Watson, GK, Perry

-- inflation from quantum fluctuation energy densities in Bloch levels

OVERVIEW

As inflation begins universe in *approximate* deS space so vacua do mix – not exact deS because of radiation from inflation beginning (e.g. something like Brandenberger-Vafa winding mode annihilation) – these set initial conditions for inflation, not entire story

Imagine general superposition of many string vacua with e.g. compact C-Y or G2 spaces, all having Standard Model gauge group, chiral fermions, but many features of compact space can be different – wave function of universe cannot be forced into one vacuum

Like Bloch's theorem for crystal – get band structure – fluctuations put universe in levels with high energy density – it relaxes down to ground state – N levels suggests $\rho \sim \rho_{in}/N$

[or, think level repulsion]

-- accompanied by emitting graviton, massless mode pairs, more radiation]

While in top level (e.g. for a few planck times) scale factor grows – in next lower level for a few planck times and scale factor grows, but less since ρ smaller – etc

Inflation effectively ends naturally after ~ hundred levels since little further growth of scale factor – graceful exit – technically ends when $\rho_{rad} > \rho_{q\ fluct}$

Basic NR quantum theory approach – to illustrate

- Particle of mass m moves in periodic potential

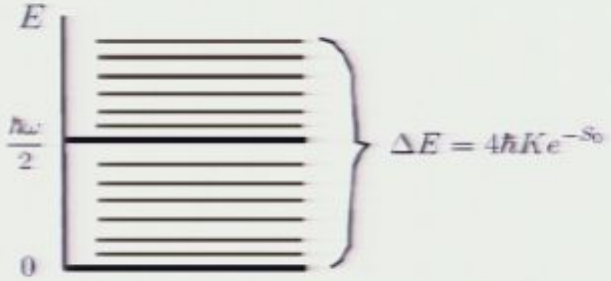
$$V(x) = V_0(1 - cos(2\pi x))/2.$$

- Bottom of each well looks like SHO with $\omega = \sqrt{2\pi^2 V_0/m}.$

- With one well would expect ground state energy $\approx \hbar\omega/2$ but real ground state has wave function non-vanishing in all wells – can calculate allowed energies with instanton methods – trial Bloch wavefunction $|\theta\rangle = \sqrt{\frac{1}{2\pi}} \sum_n e^{in\theta} |n\rangle$

- Consider $\mathcal{M}_{\theta',\theta} = \langle\theta'|e^{-HT/\hbar}|\theta\rangle \qquad \mathcal{M}_{\theta',\theta} \to \delta(\theta' - \theta)e^{-E(\theta)T/\hbar}$

- Evaluate by WKB → energy spectrum $E(\theta) = \frac{\hbar\omega}{2} - 2\hbar K \cos\theta e^{-S_0/\hbar}$
- Calculate *K*, lowest level ~ 0



- level splitting $\frac{\Delta E}{N}$

OVERVIEW CONTINUED

If in AdS space no connections between vacua, so mechanism turns off, so lowest level still deS – don't know enough to calculate whether lowest level ~ observed dark energy, but expect its energy density much less than quantum fluctuation level of particular vacua – if $\rho_{in} \sim H^2 M_{PL}^2$ then need $N_{eff} \sim 10^{90}$ in superposition at beginning – wave function samples many vacua so it will end up in vacua with small or smallest positive energy density

Decoherence from radiation, gravity interactions, etc – end up with smaller superposition – connections of vacua suppressed as universe cools – we live in a string vacuum, but probably a superposition of "symmetry" eigenstates

Inflation very different from usual description – NO SCALAR FIELD INFLATONS -- hot – ends naturally after few hundred planck times – no reheating, initial plus gradual radiation during relaxation – hot radiation filled universe emerges – enough efolds – density fluctuations OK

In addition to assumptions, basically one parameter Γ for decay width of levels – initially take constant

– if Γ too small just stays in top level, inflation does not turn off

– if Γ too large decay too rapid, not enough inflation

-- get nearly scale invariant spectrum of density and tensor perturbations

– later allow Γ time dependent, calculate Γ

No unnatural parameter fine tunings – e.g. naïve Γ can work

OVERVIEW

As inflation begins universe in *approximate* deS space so vacua do mix – not exact deS because of radiation from inflation beginning (e.g. something like Brandenberger-Vafa winding mode annihilation) – these set initial conditions for inflation, not entire story

Imagine general superposition of many string vacua with e.g. compact C-Y or G2 spaces, all having Standard Model gauge group, chiral fermions, but many features of compact space can be different – wave function of universe cannot be forced into one vacuum

Like Bloch's theorem for crystal – get band structure – fluctuations put universe in levels with high energy density – it relaxes down to ground state – N levels suggests $\rho \sim \rho_{in}/N$

[or, think level repulsion]

-- accompanied by emitting graviton, massless mode pairs, more radiation]

While in top level (e.g. for a few planck times) scale factor grows – in next lower level for a few planck times and scale factor grows, but less since ρ smaller – etc

Inflation effectively ends naturally after ~ hundred levels since little further growth of scale factor – graceful exit – technically ends when $\rho_{rad} > \rho_{q\ fluct}$

OVERVIEW CONTINUED

If in AdS space no connections between vacua, so mechanism turns off, so lowest level still deS – don't know enough to calculate whether lowest level ~ observed dark energy, but expect its energy density much less than quantum fluctuation level of particular vacua – if $\rho_{in} \sim H^2 M_{PL}^2$ then need $N_{eff} \sim 10^{90}$ in superposition at beginning – wave function samples many vacua so it will end up in vacua with small or smallest positive energy density

Decoherence from radiation, gravity interactions, etc – end up with smaller superposition – connections of vacua suppressed as universe cools – we live in a string vacuum, but probably a superposition of "symmetry" eigenstates

Inflation very different from usual description – NO SCALAR FIELD INFLATONS -- hot – ends naturally after few hundred planck times – no reheating, initial plus gradual radiation during relaxation – hot radiation filled universe emerges – enough efolds – density fluctuations OK

In addition to assumptions, basically one parameter Γ for decay width of levels – initially take constant

– if Γ too small just stays in top level, inflation does not turn off

– if Γ too large decay too rapid, not enough inflation

-- get nearly scale invariant spectrum of density and tensor perturbations

– later allow Γ time dependent, calculate Γ

No unnatural parameter fine tunings – e.g. naïve Γ can work

Pirsa: 08090047

Radiation (gravitons, massless string states) emitted from transitions to lower levels, plus initial amount

Inflation ends when $\rho_\Lambda \approx \rho_{rad}$, and $\rho_\Lambda \approx \rho_{\Lambda,0} e^{-\Gamma t}$,

so $\rho_{rad,end} \approx \rho_{\Lambda,0} e^{-\Gamma t_{end}}$

Number of efolds about $Ht_{end} \approx 60$, so $\rho_{rad,end} \sim \rho_{\Lambda,0} e^{-3}$

$$3H^2 = \frac{8\pi}{M_p^2}(\rho_\Lambda + \rho_r),$$

$$\frac{\ddot{a}}{a} = \frac{8\pi}{3M_p^2}(\rho_\Lambda - \rho_r),$$

$$\dot{\rho}_\Lambda = -\Gamma \rho_\Lambda,$$

$$\dot{\rho}_r = -4H\rho_r + \Gamma \rho_\Lambda.$$

-- Radiation can be helpful in avoiding overshoot problem for stabilizing moduli [Brustein, de Alwis, Martens th/0408160]

Basic NR quantum theory approach – to illustrate

- Particle of mass m moves in periodic potential

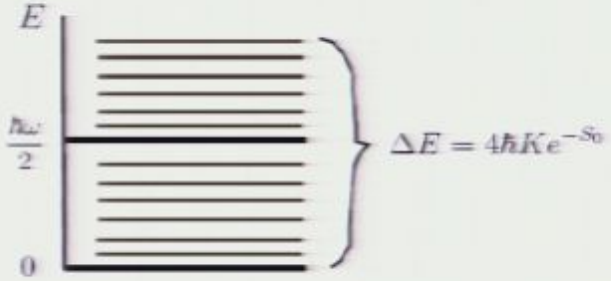
$$V(x) = V_0(1 - cos(2\pi x))/2.$$

- Bottom of each well looks like SHO with $\omega = \sqrt{2\pi^2 V_0/m}.$

- With one well would expect ground state energy $\approx \hbar\omega/2$ but real ground state has wave function non-vanishing in all wells – can calculate allowed energies with instanton methods – trial Bloch wavefunction $|\theta\rangle = \sqrt{\frac{1}{2\pi}} \sum_n e^{in\theta} |n\rangle$

- Consider $\mathcal{M}_{\theta',\theta} = \langle\theta'|e^{-HT/\hbar}|\theta\rangle \qquad \mathcal{M}_{\theta',\theta} \to \delta(\theta' - \theta)e^{-E(\theta)T/\hbar}$

- Evaluate by WKB → energy spectrum $E(\theta) = \frac{\hbar\omega}{2} - 2\hbar K \cos\theta e^{-S_0/\hbar}$
- Calculate *K*, lowest level ~ 0



Pirsa: 08090047

- level splitting $\frac{\Delta E}{N}$

For our case:

- Minima not points in physical space, rather particular (e.g. Calabi-Yau) spaces corresponding to a particular vacuum state – each has SM gauge group, approximate couplings, three famililes etc but different hidden U(1) charges, interchanges of moduli in gauge kinetic function, brane-antibrane pairs, etc

- Usual use of instantons is as mechanism so universe can start in some vacuum and evolve to a different one – here not spacetime tunneling but a mechanism for a non-perturbative calculation of the energy spectrum

Generalize to field theory

- Energy → energy density
- Eigenstates of Hamiltonian will have wave functions spread out over many minima – Hawking-Moss tunneling removes degeneracies, pushing levels up and down repeatedly
- Suppose potential consists of d-dimensional hypercube lattice of minima in field space – d determined by which minima can communicate with each other via instantons (not usual tunneling) – separate θ for each direction – repeat calculation

$$\rho(\{\theta_i\}) = \rho_0 - 2\sum_i^d K\cos\theta_i\, e^{-S_0/\hbar}$$

- So ground state $\rho_{min} = \rho_0 - 2Kde^{-S_0/\hbar}$
- Cannot calculate ρ_{min} yet, assume small

Superpositions, decoherence

- As inflation begins, in 4D world – wave function is superposition of states with Standard Model, trace over many unobserved degrees of freedom of 6D or 7D world, string excitations, KK modes from compactification, U(1) charges, etc, etc
- Degeneracies are surely present, not enough known about string vacua to give up
- Two issues – early superposition – late coherence, as inflation ends
- If late transitions rapid enough perhaps they preserve the superposition properties as a relic of the superposition era
- Dienes, Thomas arXiv:0806.3364

COMMENTS AND CONCLUSIONS?

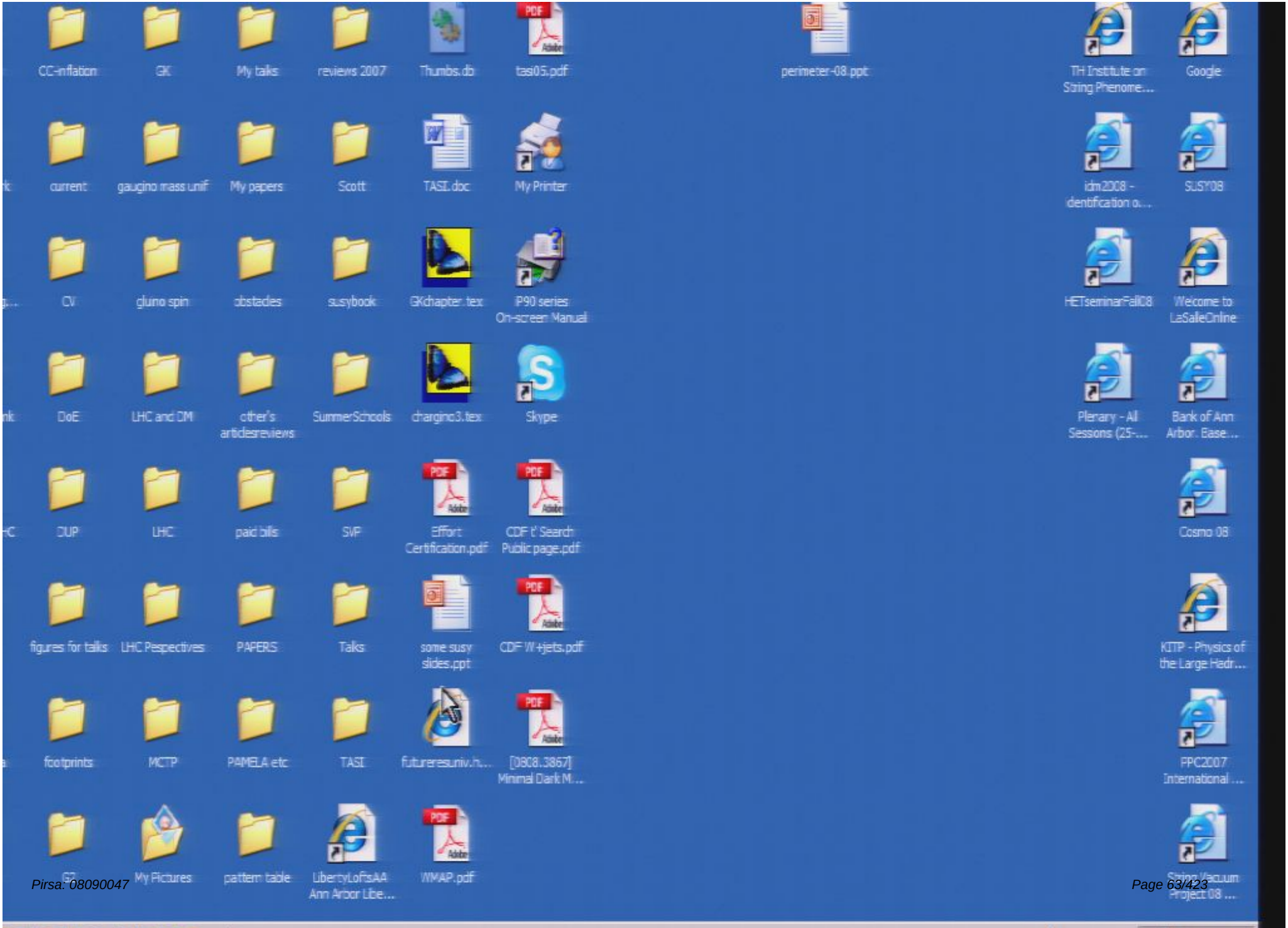
- Understanding our string vacuum, i.e. calculating the most important observables, seems to require a large number of vacua with same low scale effective theory – one part of "multiverse"
  -- 10^{90} (10^{40} ?) seems consistent with total size $\sim 10^{\text{few hundred}}$
- String theory testable in our string vacuum – many testable predictions – like F=ma
- In string theory multiverse can have implications for conventional observables like LHC ones
- Reductionist – string theory provides a *meaningful* ground state from which we can build up all we see – espresso, dinosaurs, stars, galaxies... -- emergence, but no mysteries – forces, particles emerge as go to 4D from 10D, big bang, hadrons, atoms, etc – "meaningful" requires multiverse

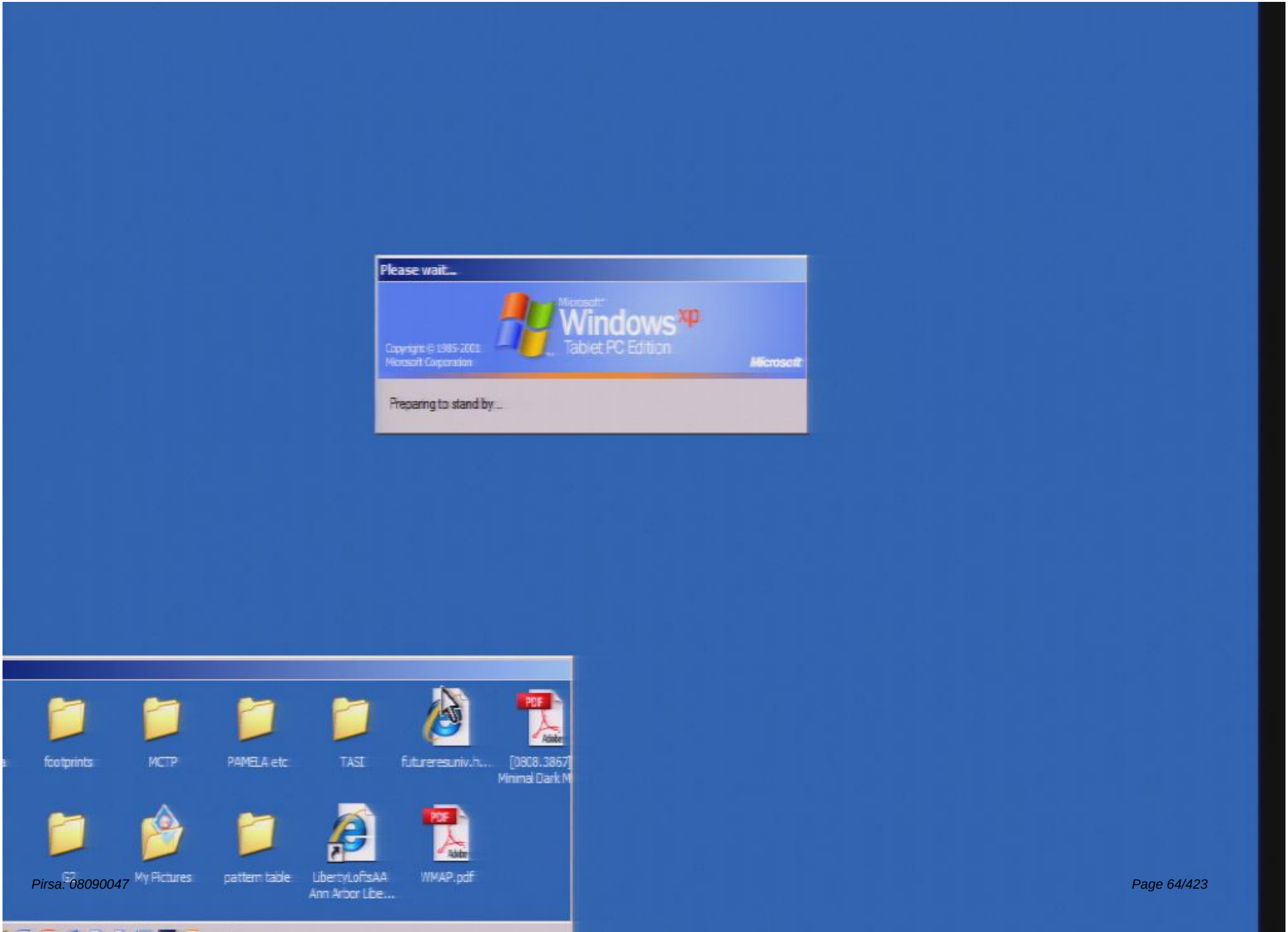
perimeter-08.ppt [Compatibility Mode] - Microsoft PowerPoint

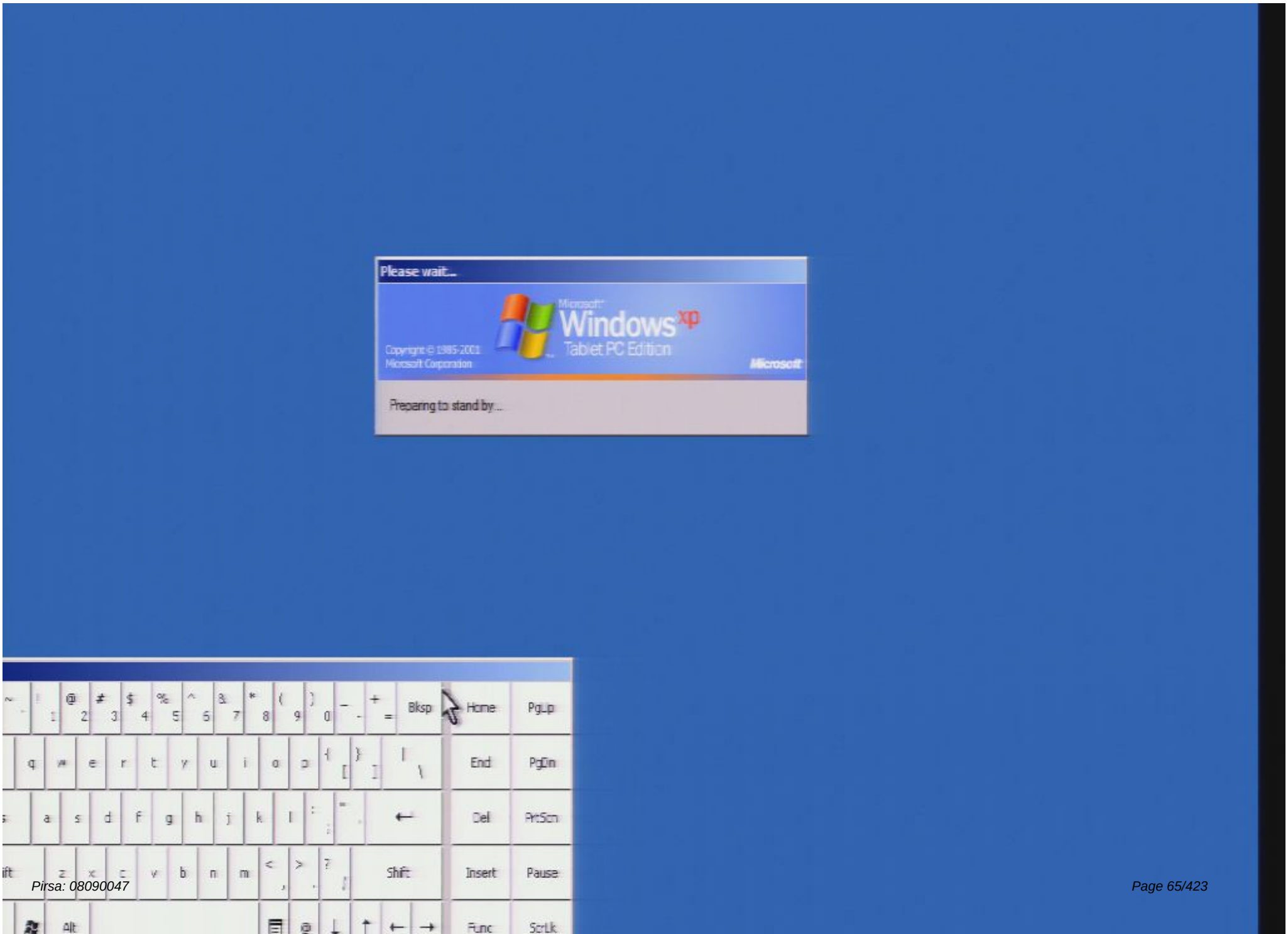
Insert Design Animations Slide Show Review View MathType Acrobat

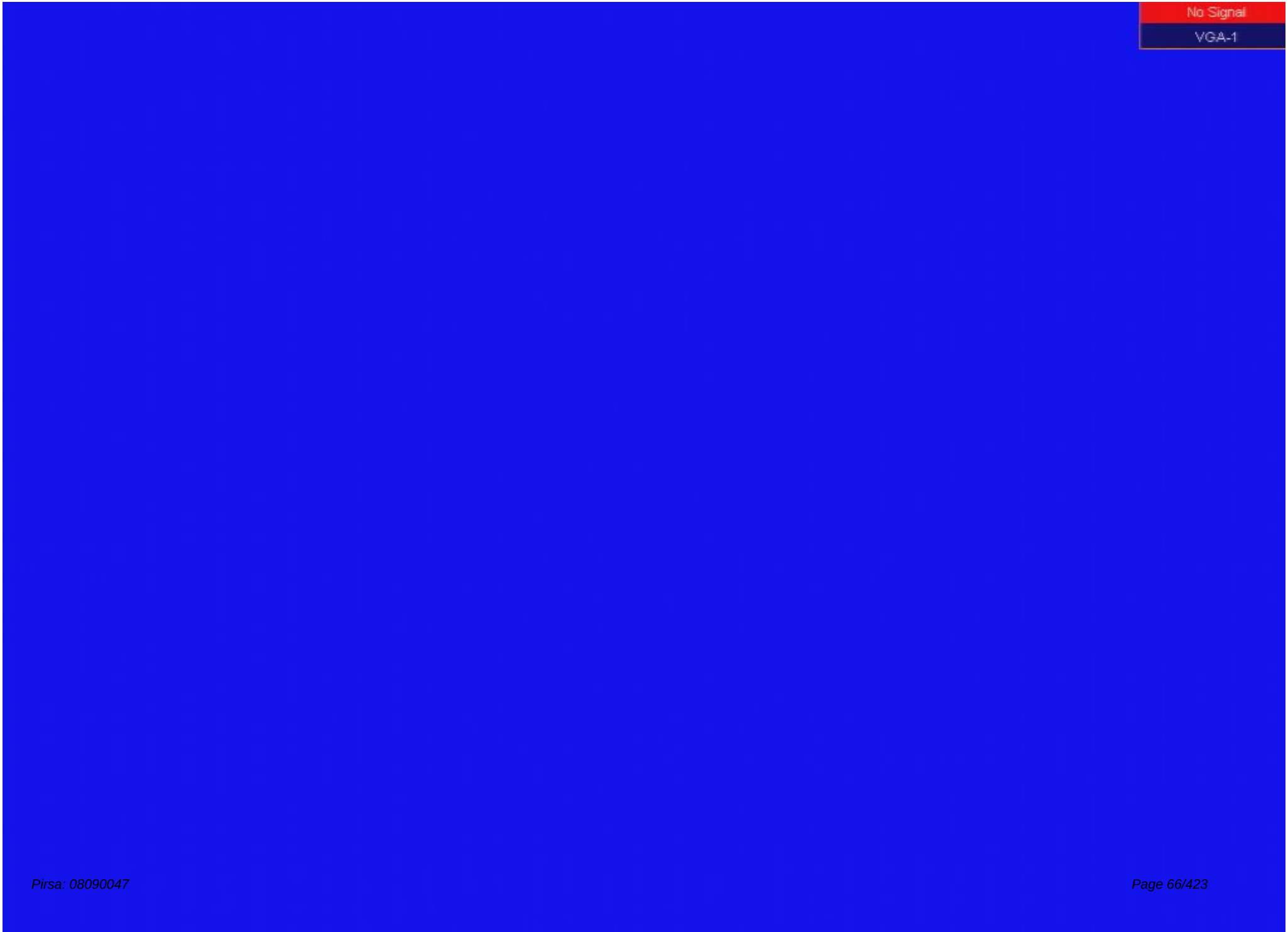
COMMENTS AND CONCLUSIONS?

- Understanding our string vacuum, i.e. calculating the most important observables, seems to require a large number of vacua with same low scale effective theory – one part of "multiverse"
  - -- 10^{90} (10^{40} ?) seems consistent with total size $\sim 10^{\text{few hundred}}$
- String theory testable in our string vacuum – many testable predictions – like F=ma
- In string theory multiverse can have implications for conventional observables like LHC ones
- Reductionist – string theory provides a *meaningful* ground state from which we can build up all we see – espresso, dinosaurs, stars, galaxies... -- emergence, but no mysteries – forces, particles emerge as go to 4D from 10D, big bang, hadrons, atoms, etc – "meaningful" requires multiverse

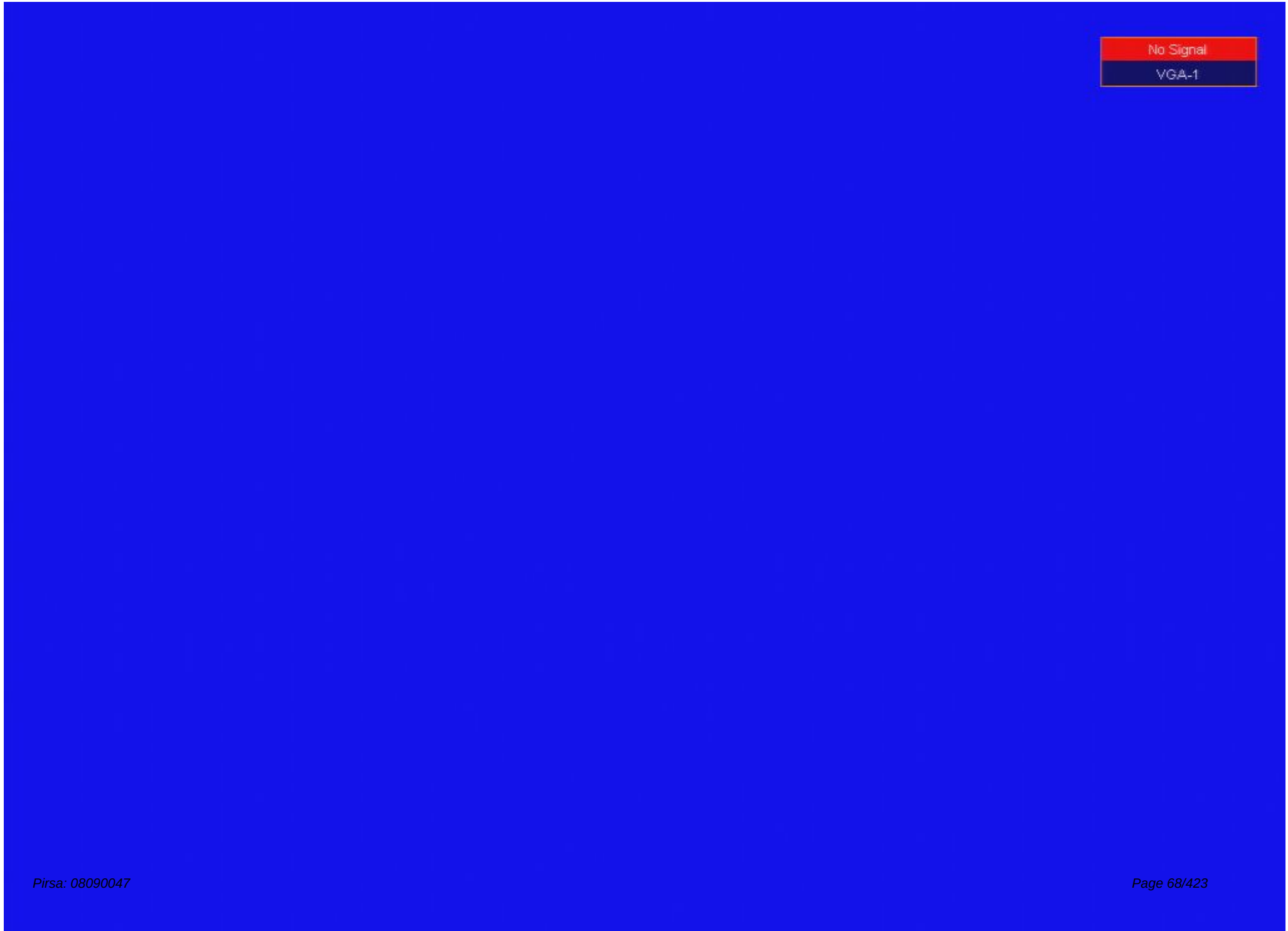

CC-inflation
GK
My talks
reviews 2007
Thumbs.db
tasi05.pdf
perimeter-08.ppt
TH Institute on String Phenome...
Google
current
gaugino mass unif
My papers
Scott
TASI.doc
My Printer
idm2008 - identification o...
SUSY08
CV
gluino spin
obstacles
susybook
GKchapter.tex
iP90 series On-screen Manual
HETseminarFall08
Welcome to LaSalleOnline
DoE
LHC and DM
other's articlesreviews
SummerSchools
chargino3.tex
Skype
Plenary - All Sessions (25-...
Bank of Ann Arbor: Ease...
DUP
LHC
paid bills
SVP
Effort Certification.pdf
CDF t' Search Public page.pdf
Cosmo 08
figures for talks
LHC Pespectives
PAPERS
Talks
some susy slides.ppt
CDF W+jets.pdf
KITP - Physics of the Large Hadr...
footprints
MCTP
PAMELA etc
TASI
futureresuniv.h...
[0808.3867] Minimal Dark M...
PPC2007 International ...
My Pictures
pattern table
LibertyLoftsAA Ann Arbor Libe...
WMAP.pdf

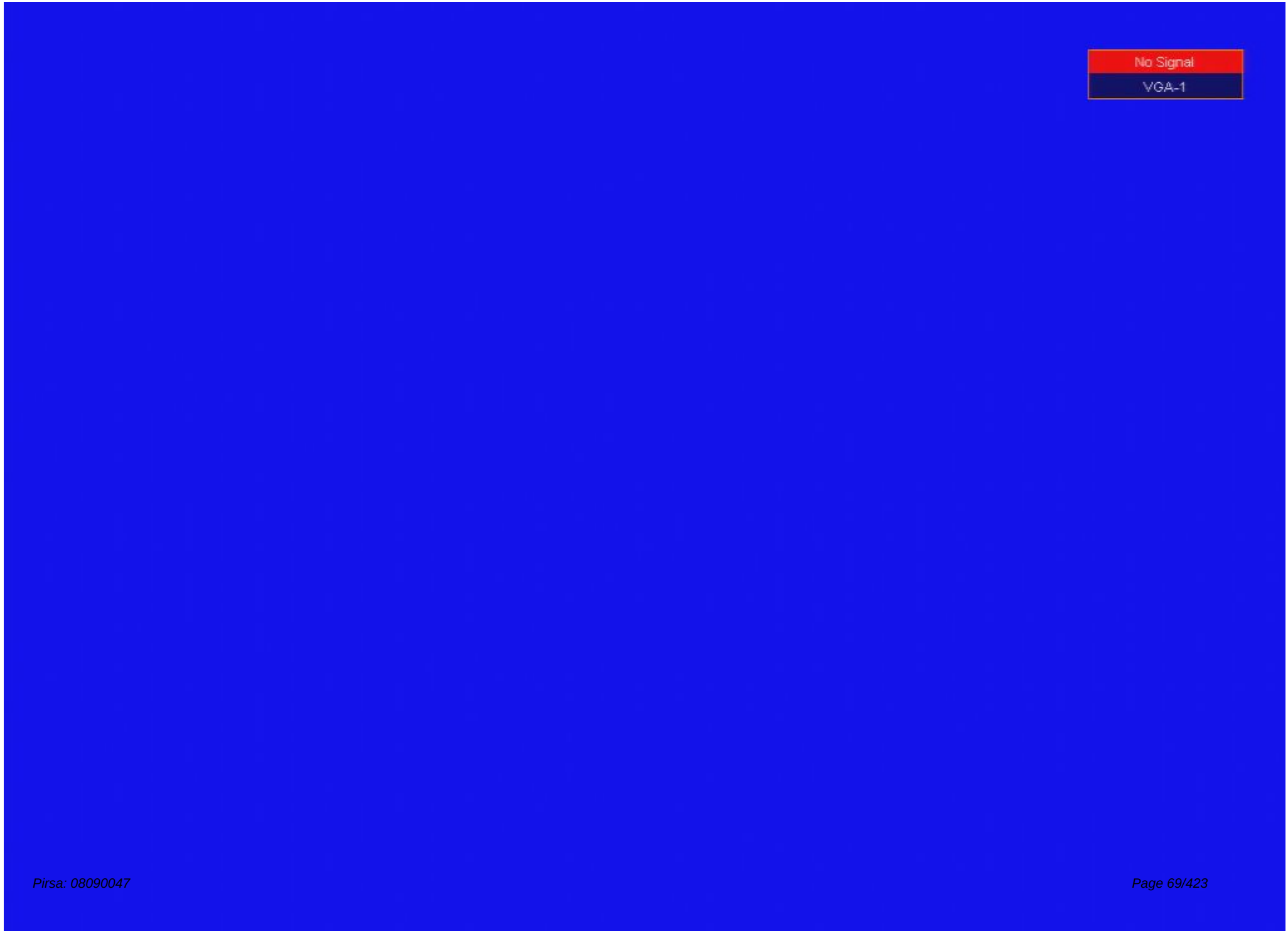

Please wait...
Microsoft
Windows xp
Tablet PC Edition
Copyright © 1985-2001
Microsoft Corporation
Microsoft
Preparing to stand by...
footprints
MCTP
PAMELA etc
TASI
futureresuniv.h...
[0808.3867]
Minimal Dark M
My Pictures
pattern table
LibertyLoftsAA
Ann Arbor Libe...
WMAP.pdf

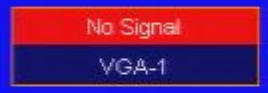

Please wait...
Microsoft
Windows xp
Tablet PC Edition
Copyright © 1985-2001
Microsoft Corporation
Microsoft
Preparing to stand by...
Bksp
Home
PgUp
End
PgDn
Del
PrtScn
Shift
Insert
Pause
Alt
Func
ScrLk

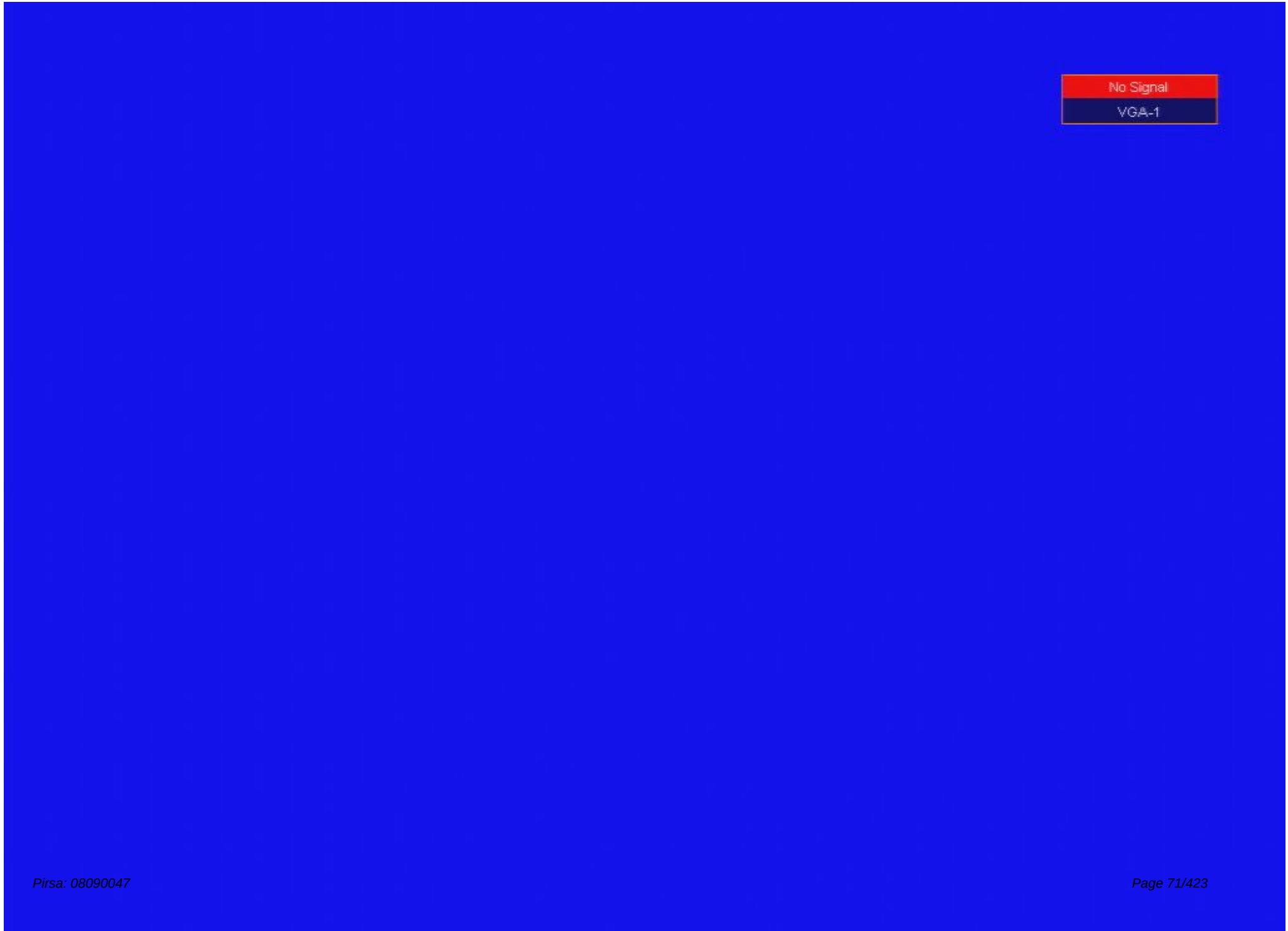

No Signal
VGA-1

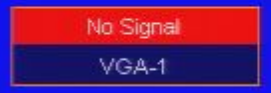

No Signal
VGA-1

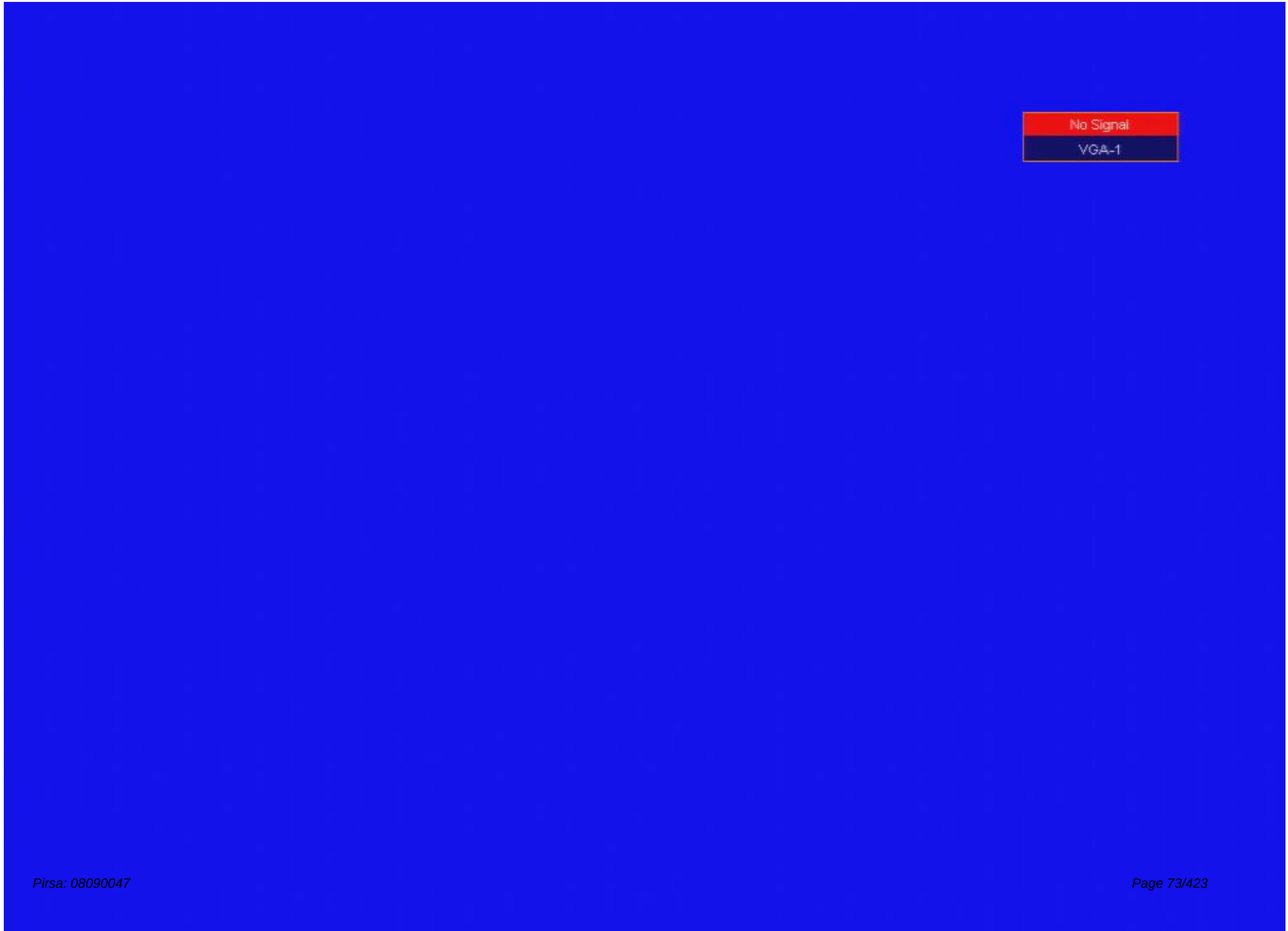

No Signal
VGA-1

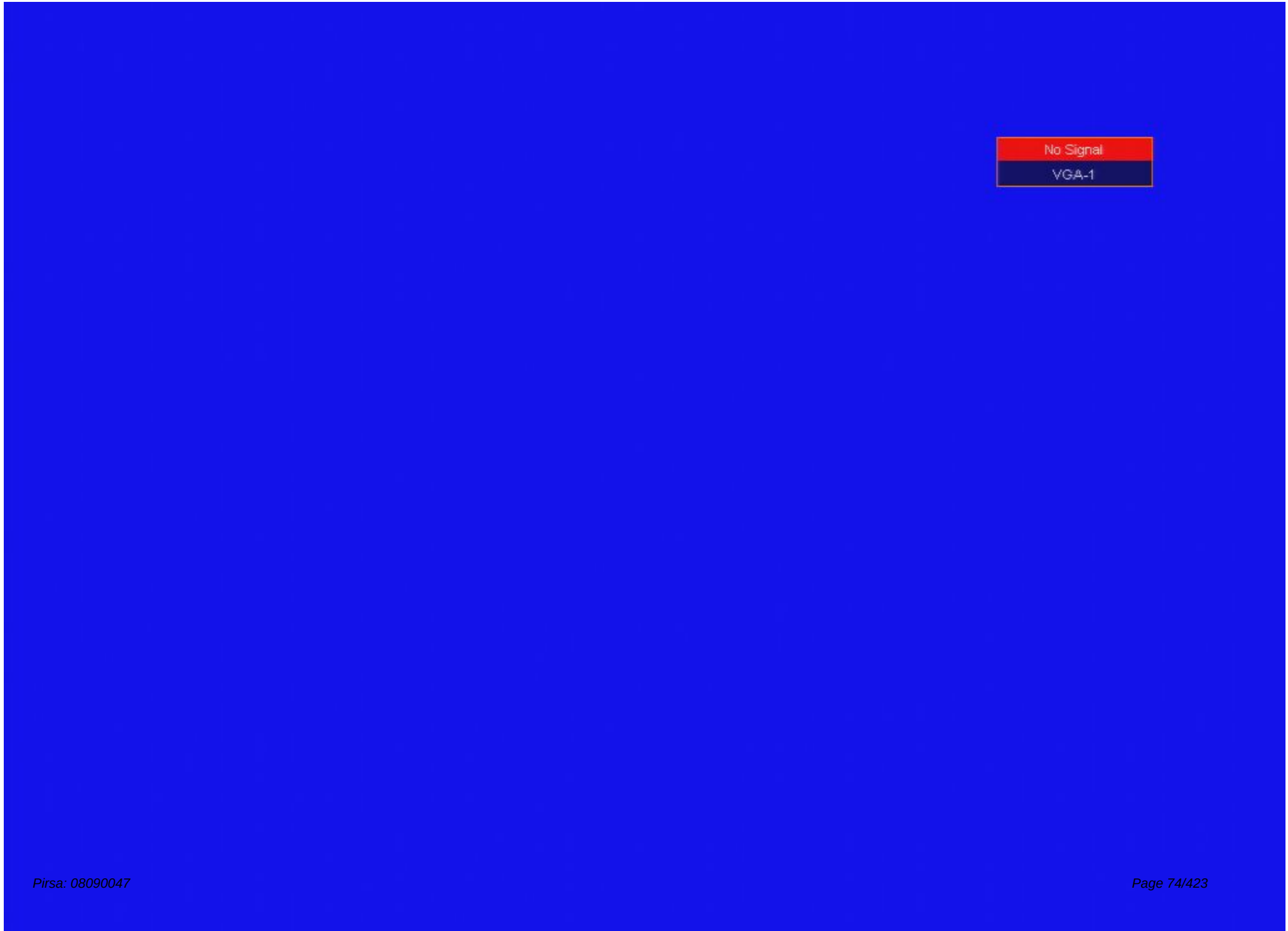

No Signal
VGA-1

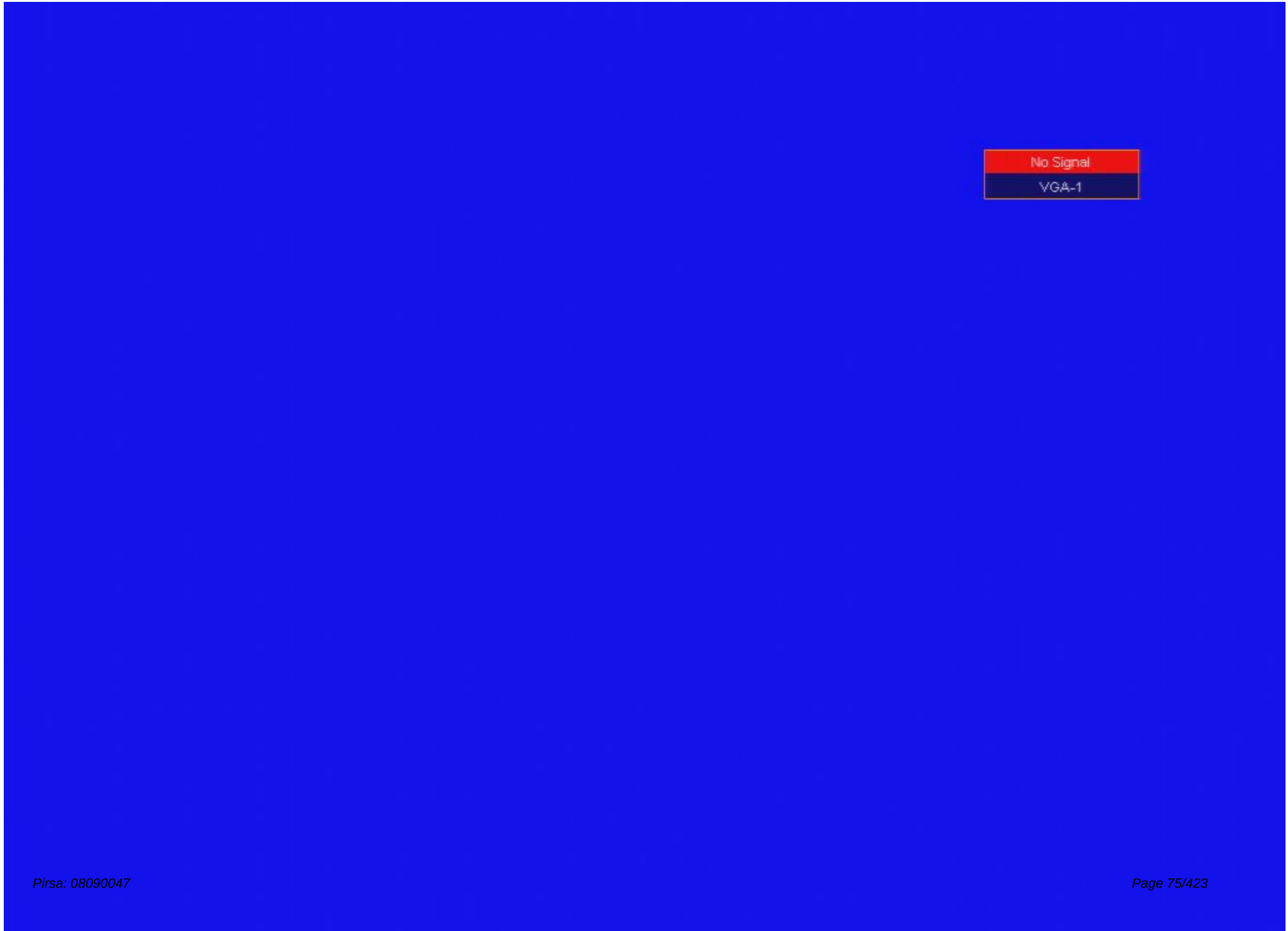

No Signal
VGA-1

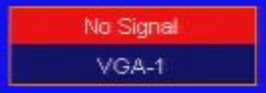

No Signal
VGA-1

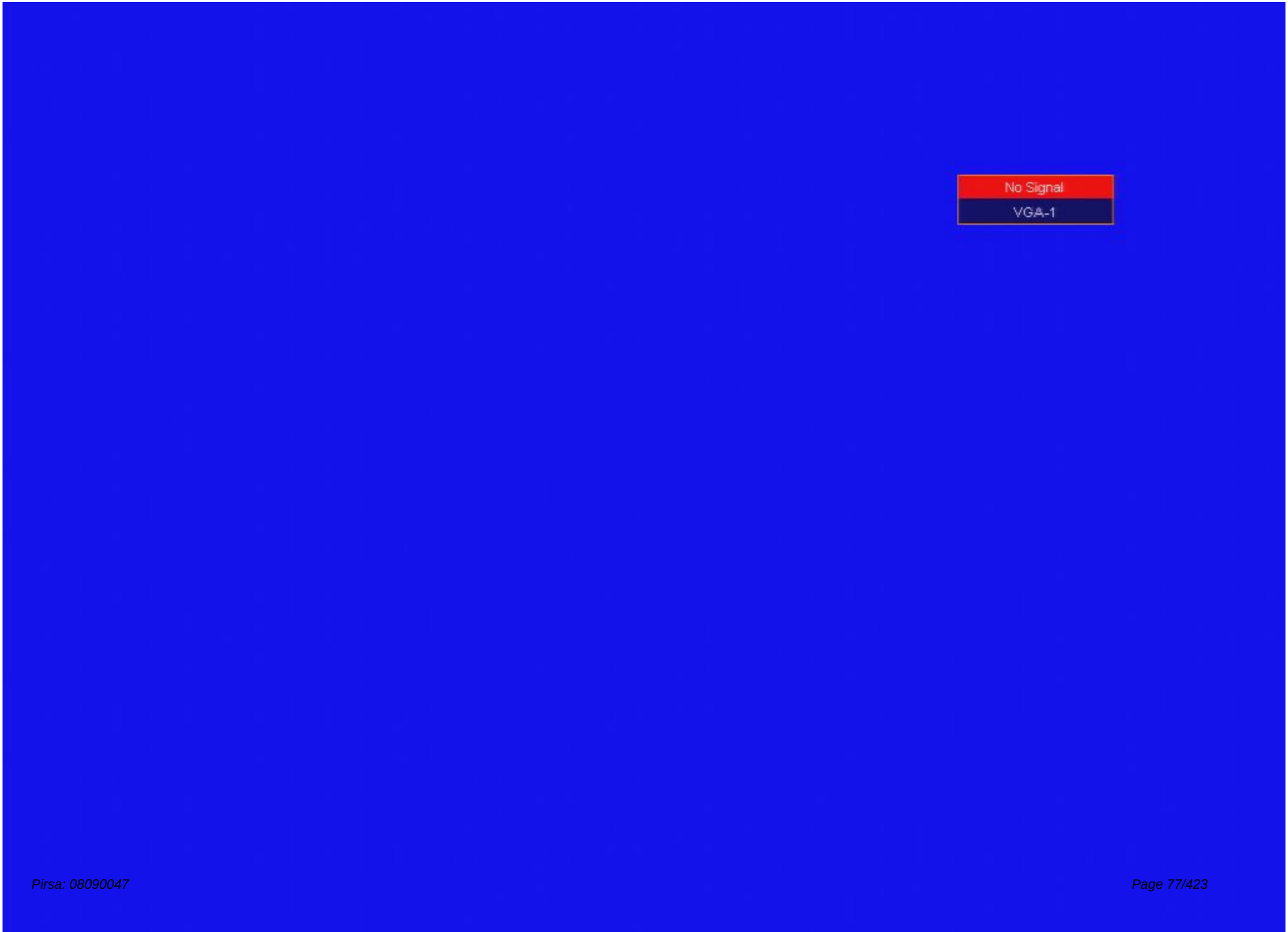

No Signal
VGA-1

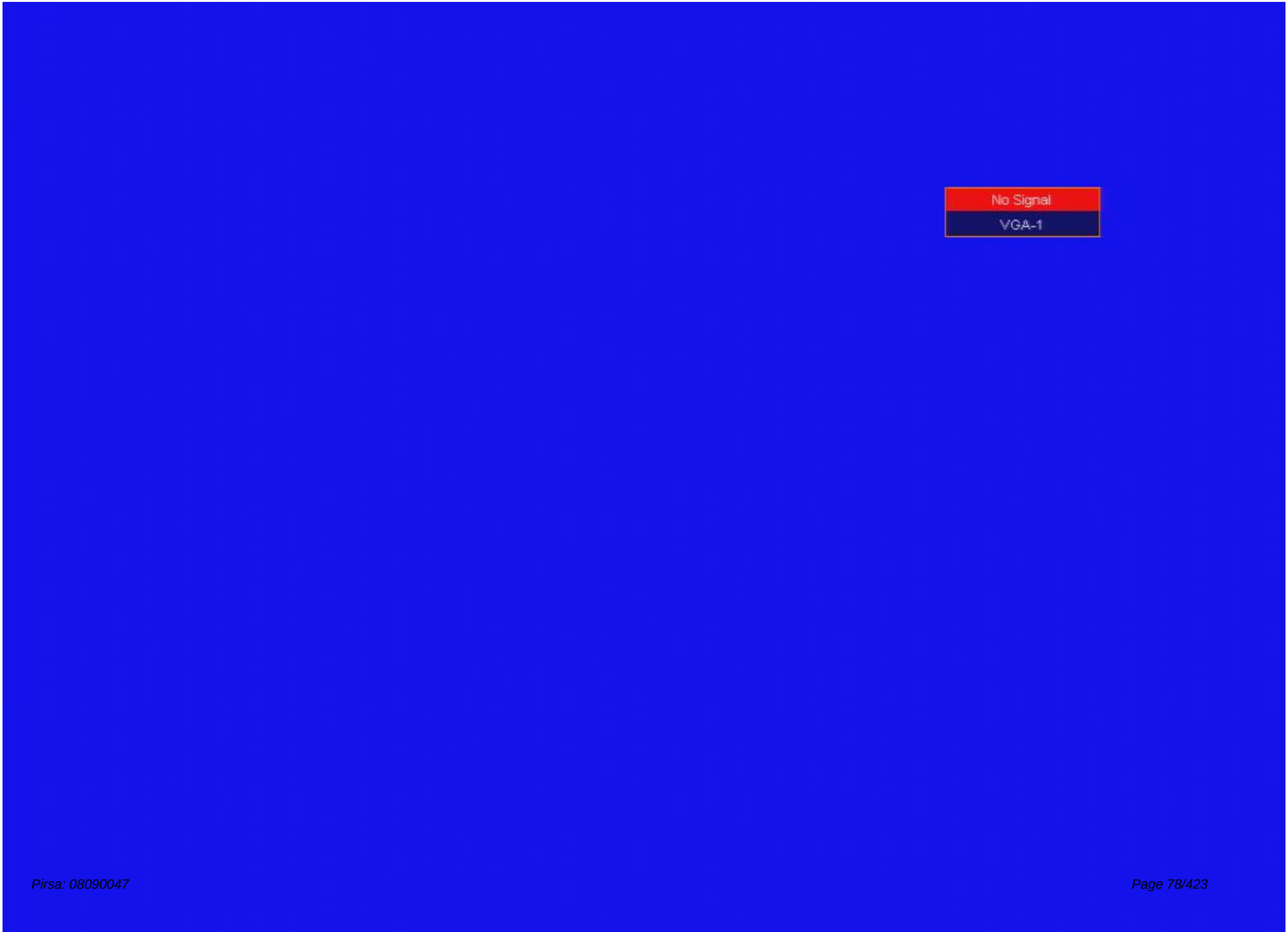

No Signal
VGA-1

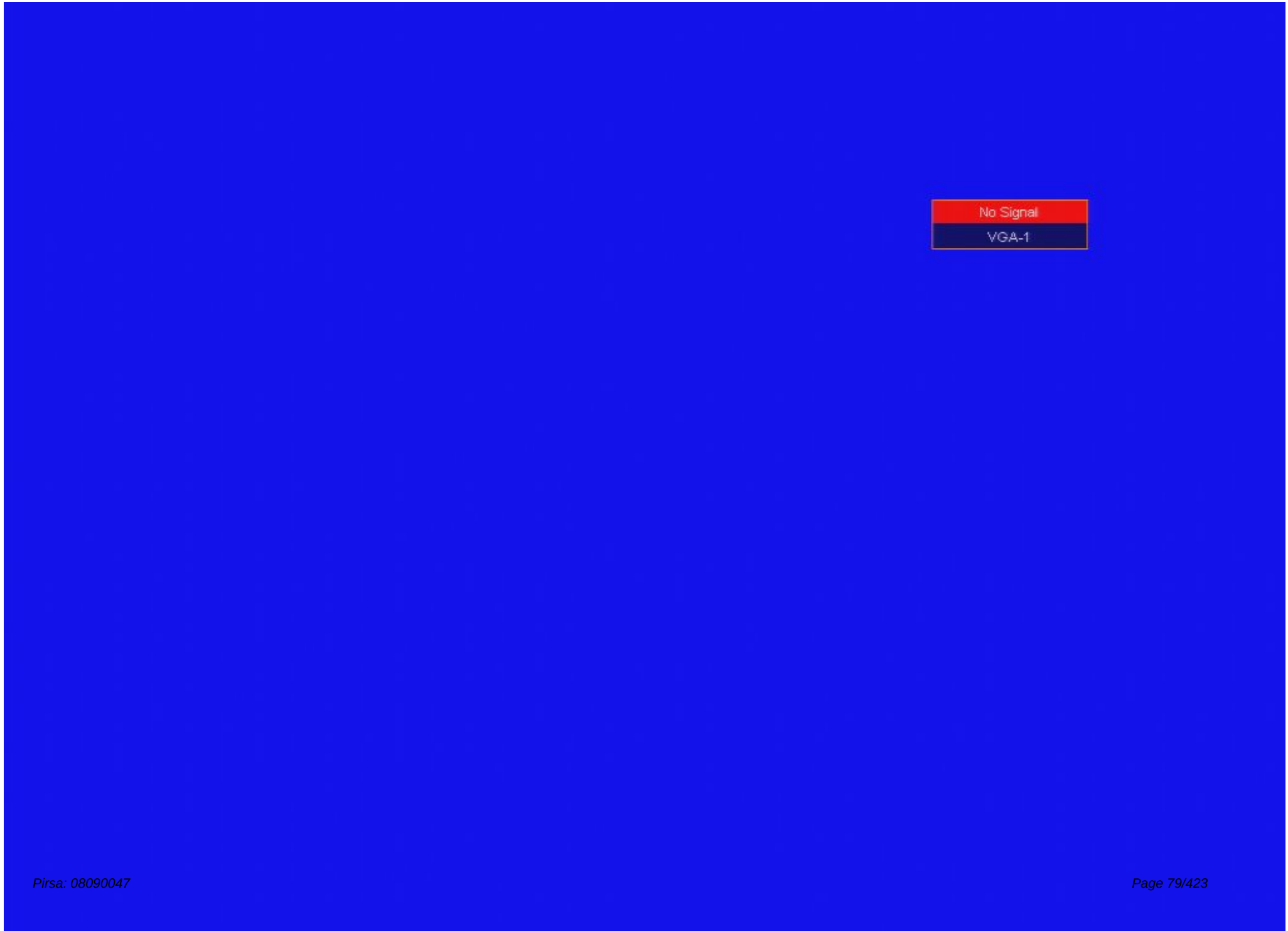

No Signal
VGA-1

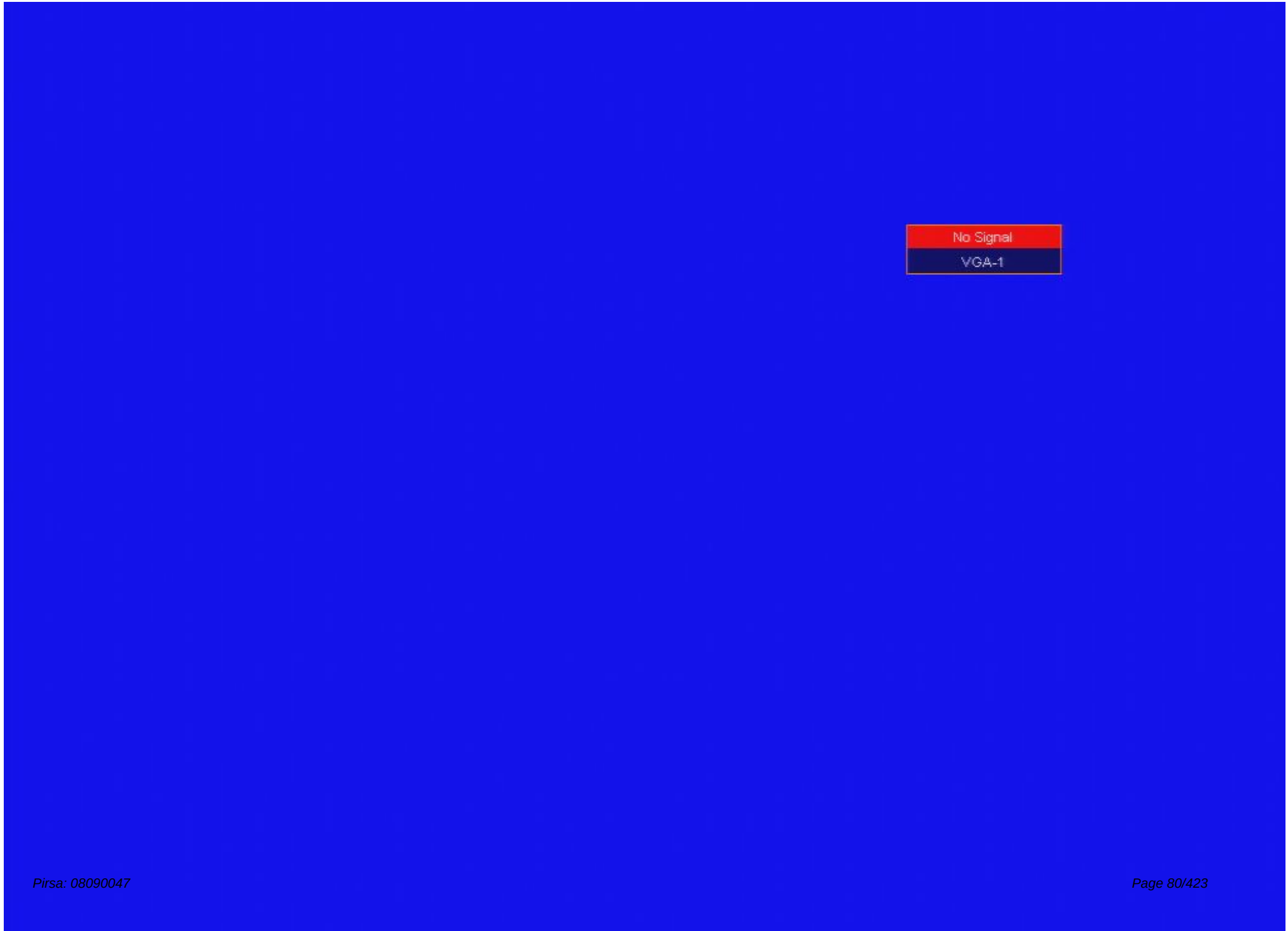

No Signal
VGA-1

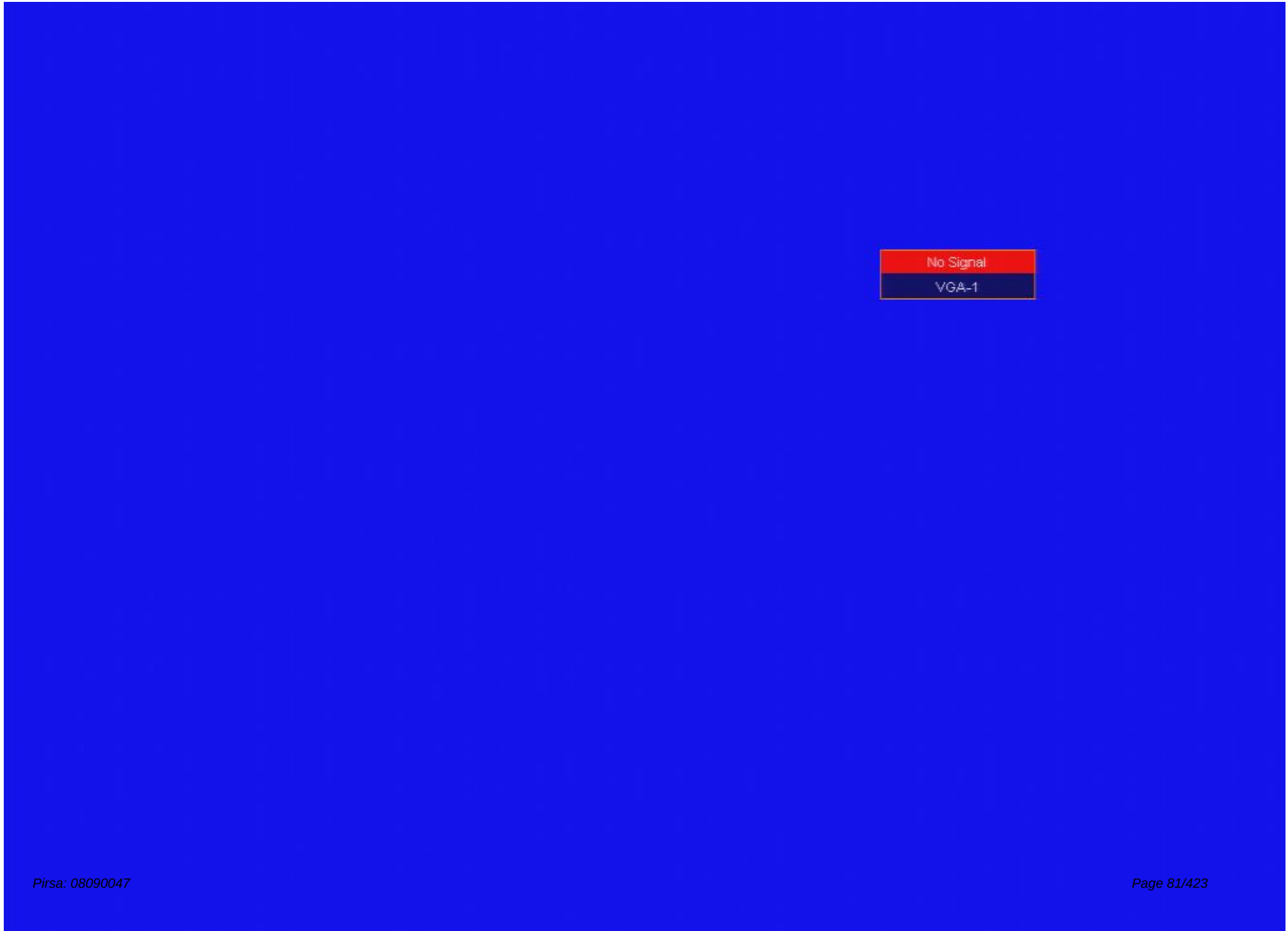

No Signal
VGA-1

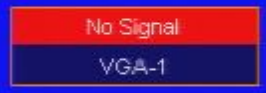

No Signal
VGA-1

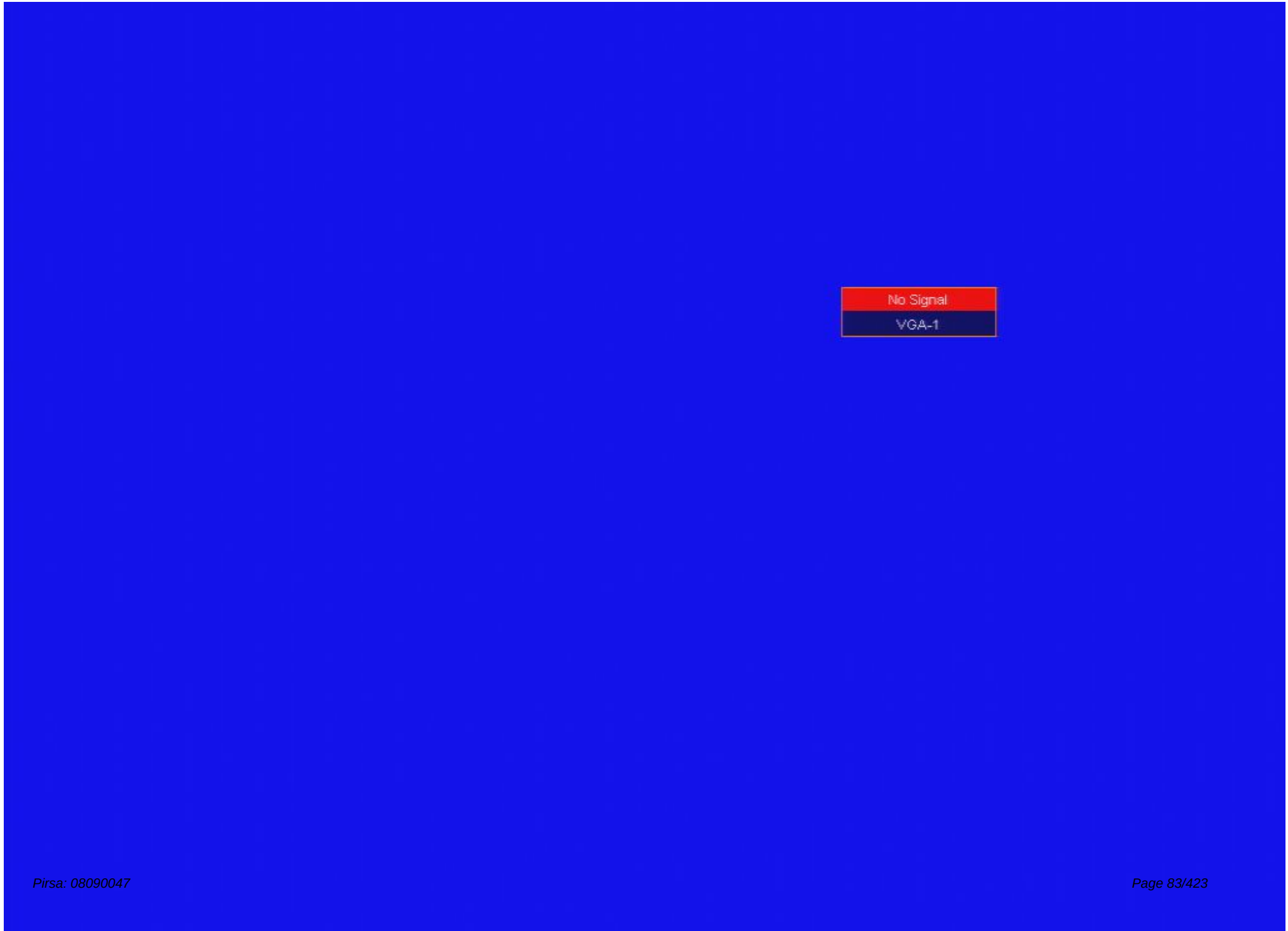

No Signal
VGA-1

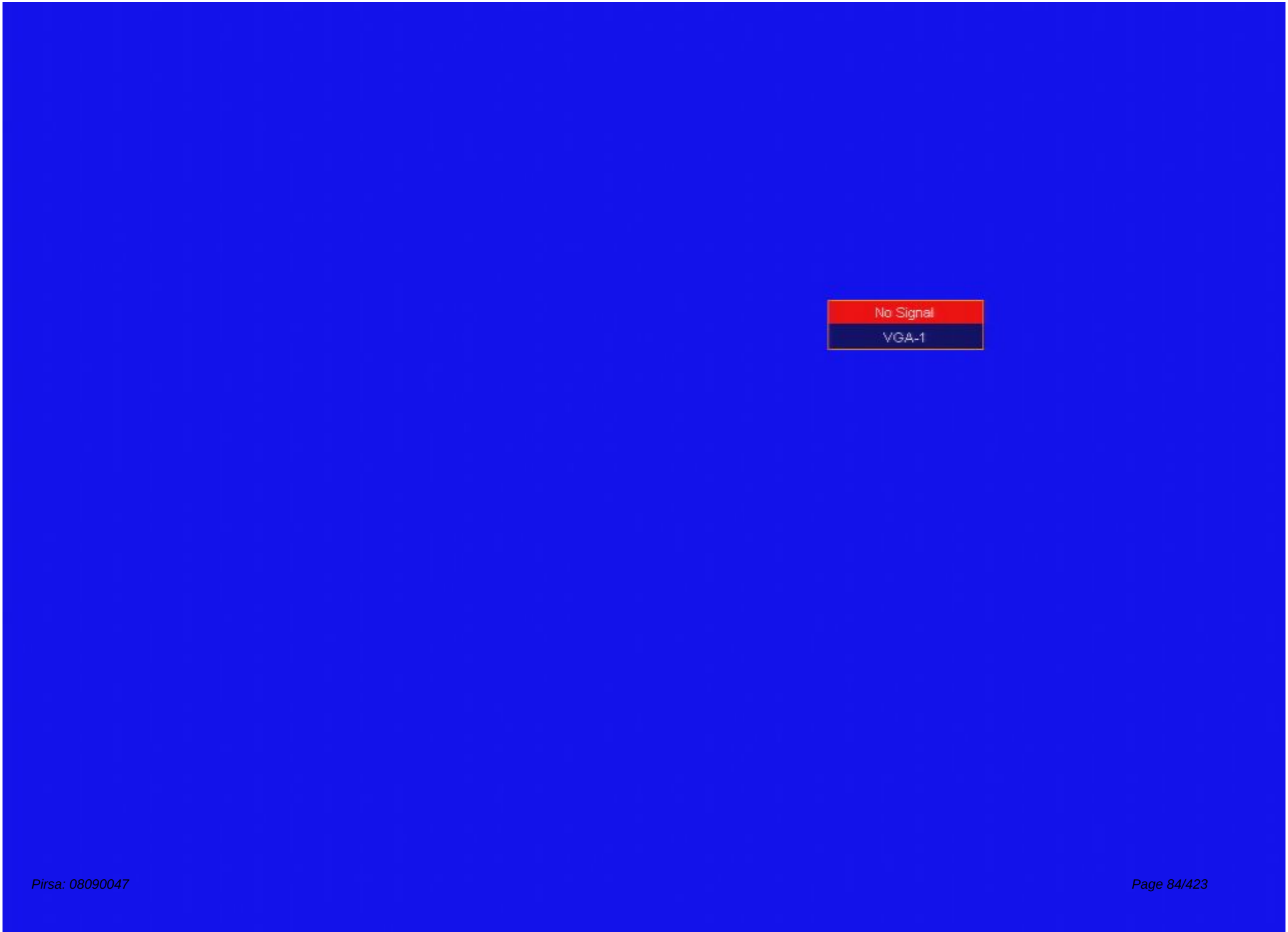

No Signal
VGA-1

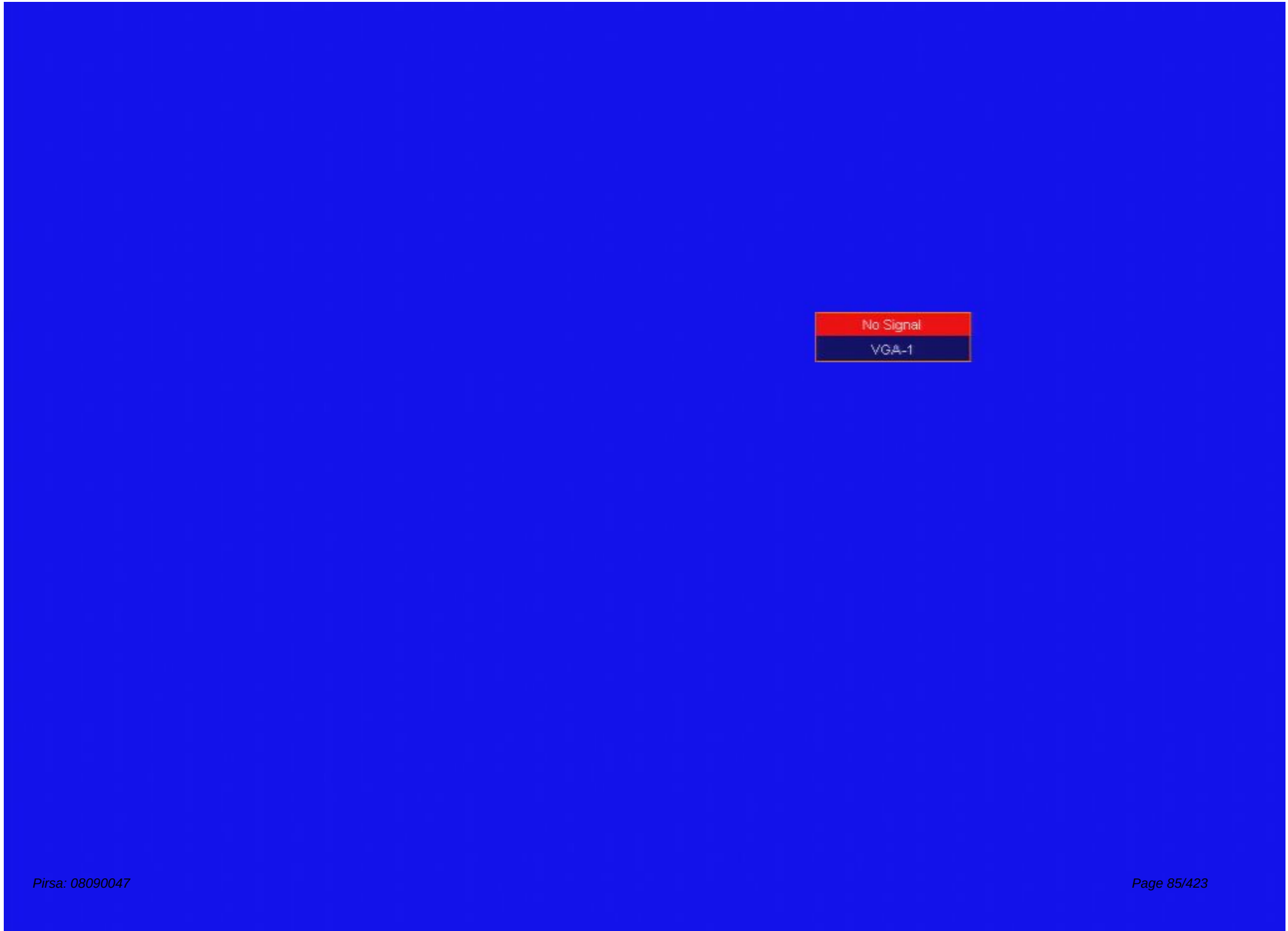

No Signal
VGA-1

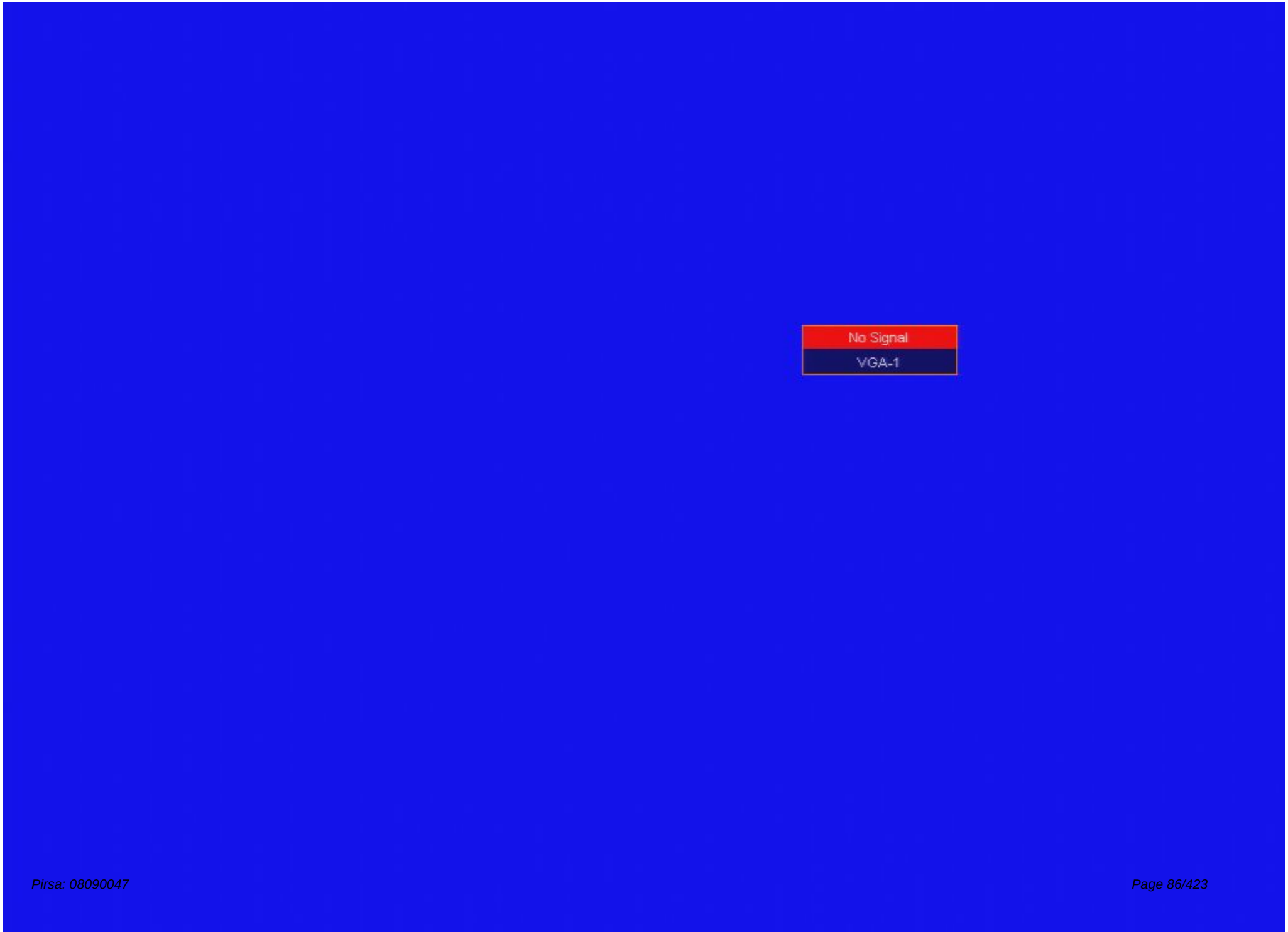

No Signal
VGA-1

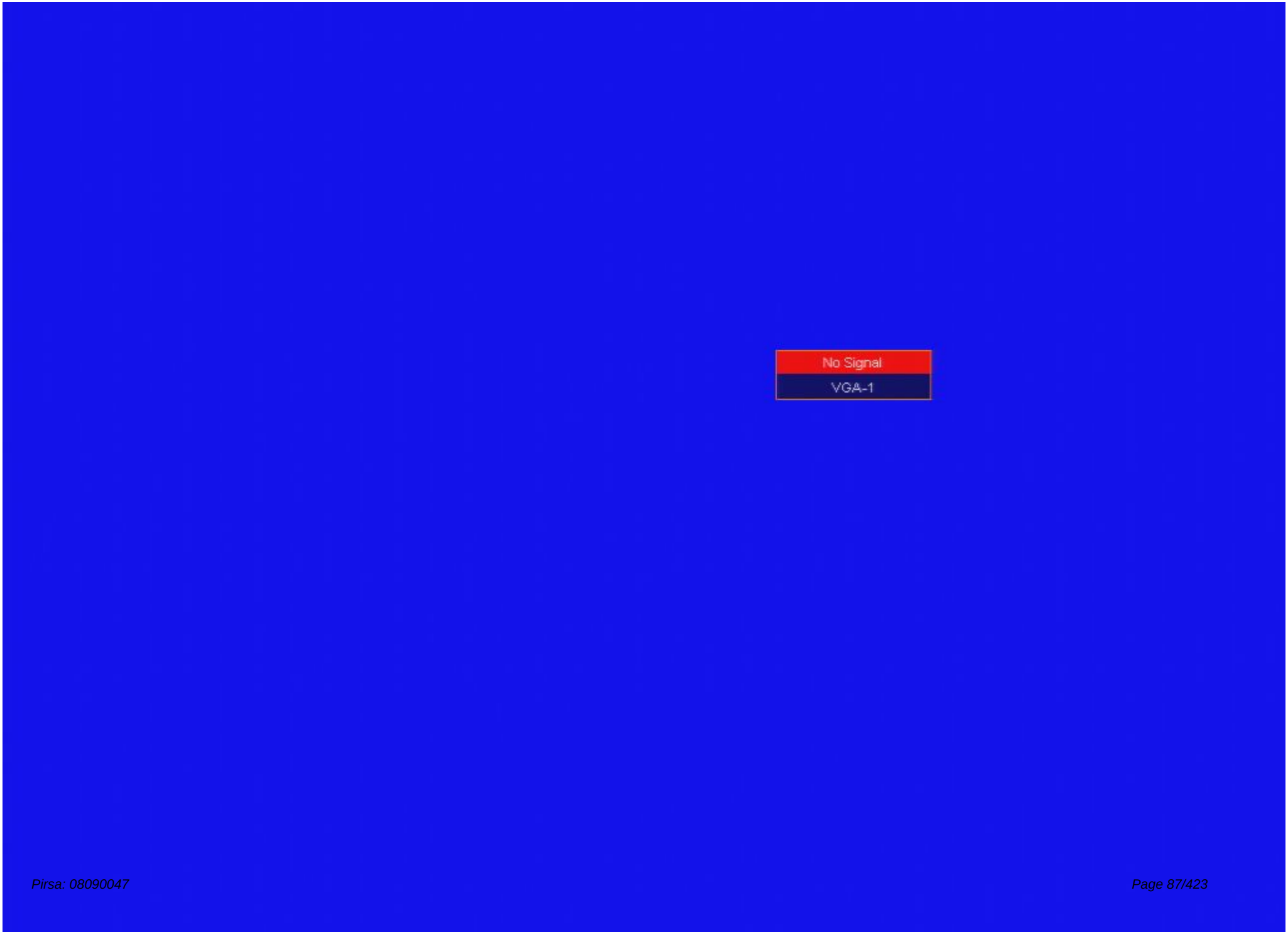

No Signal
VGA-1

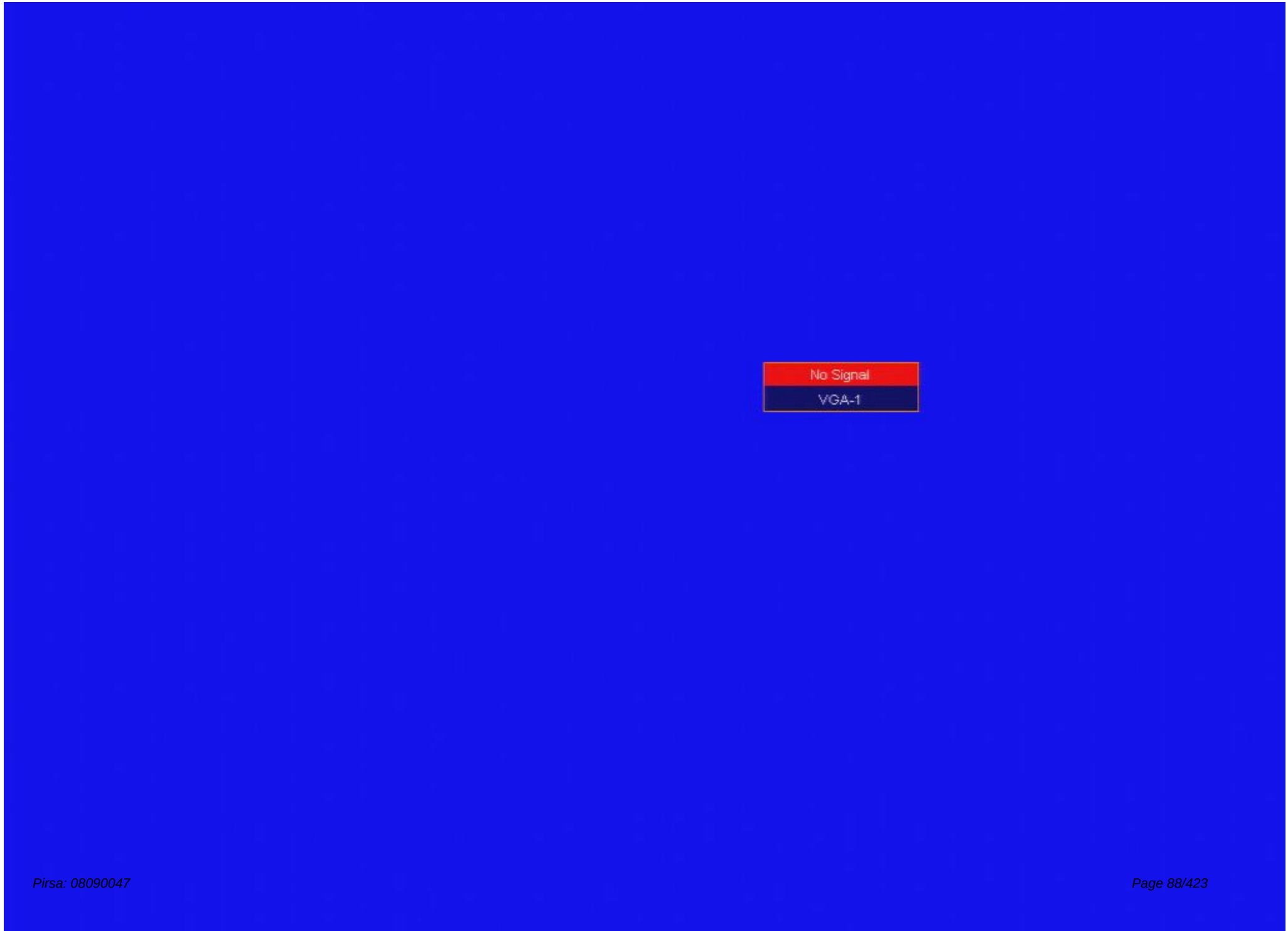

No Signal
VGA-1

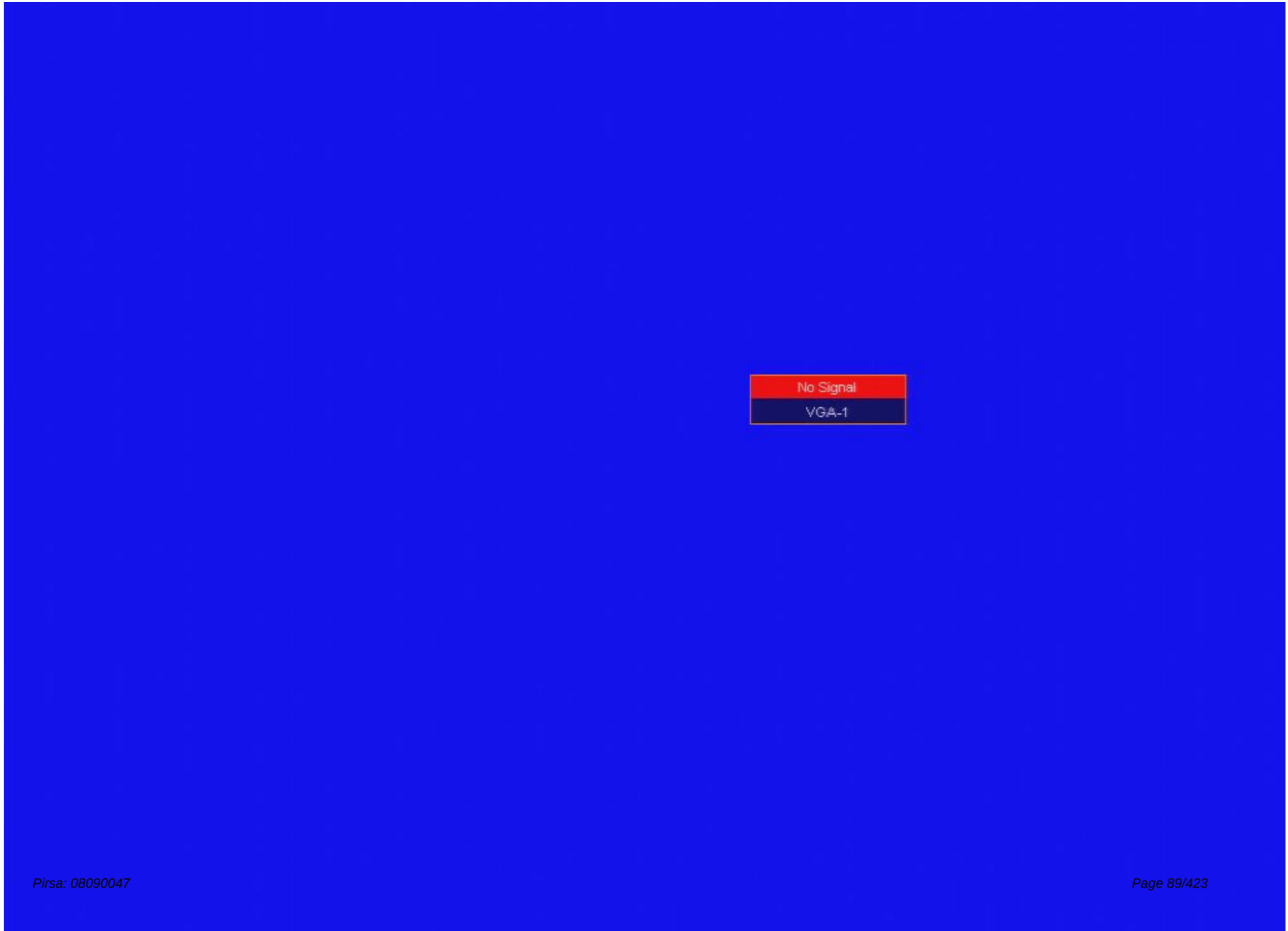

No Signal
VGA-1

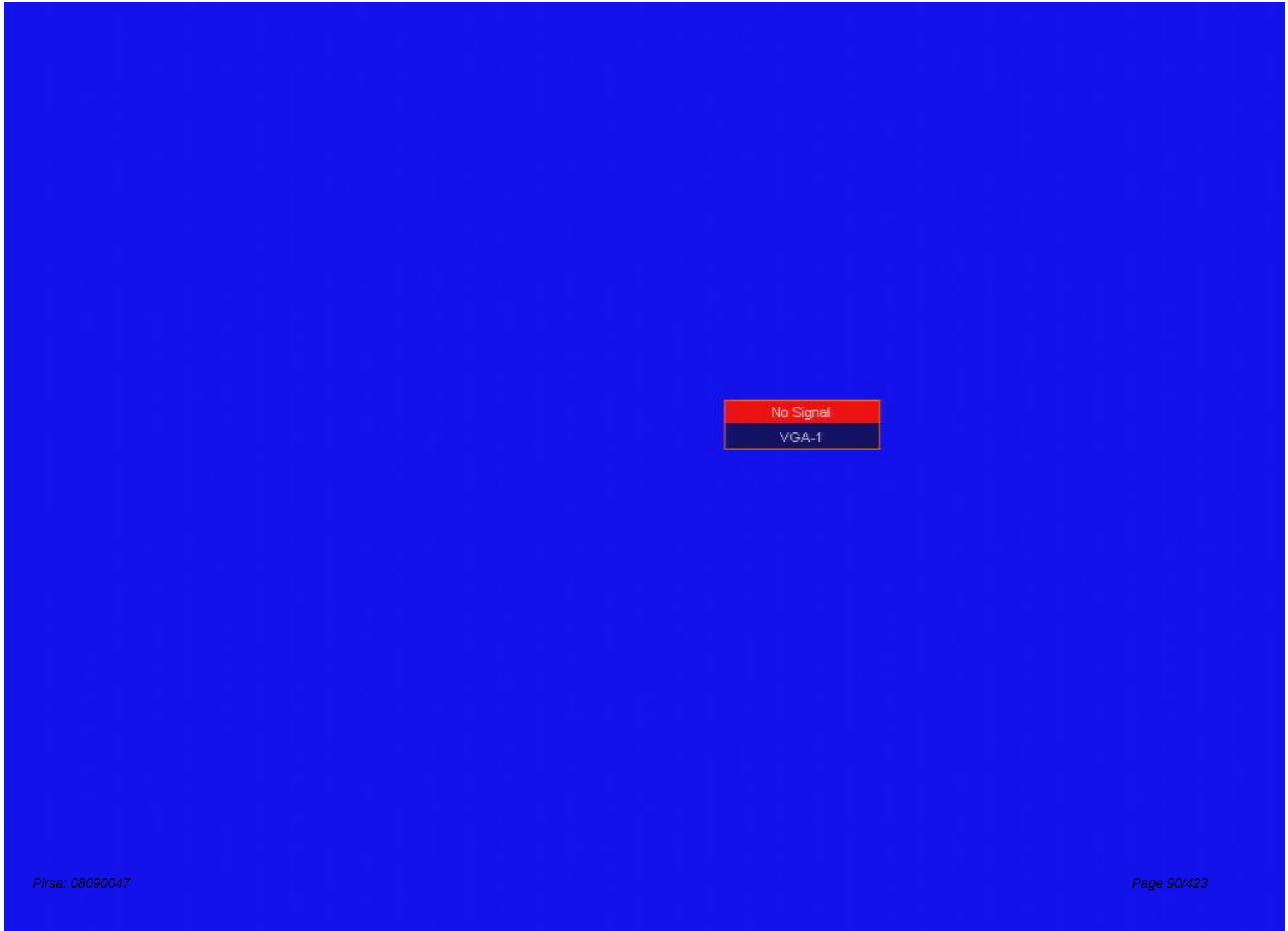

No Signal
VGA-1

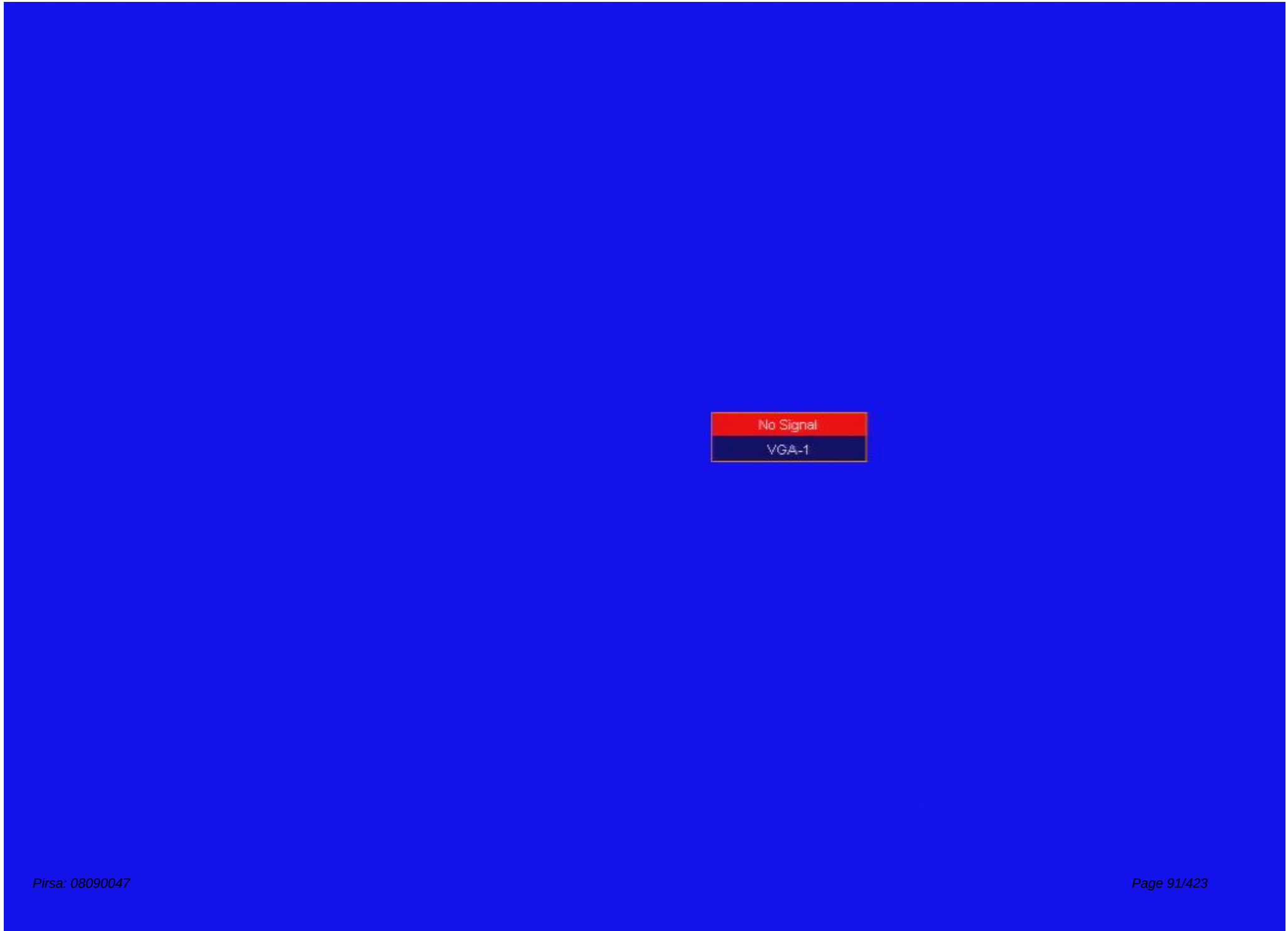

No Signal
VGA-1

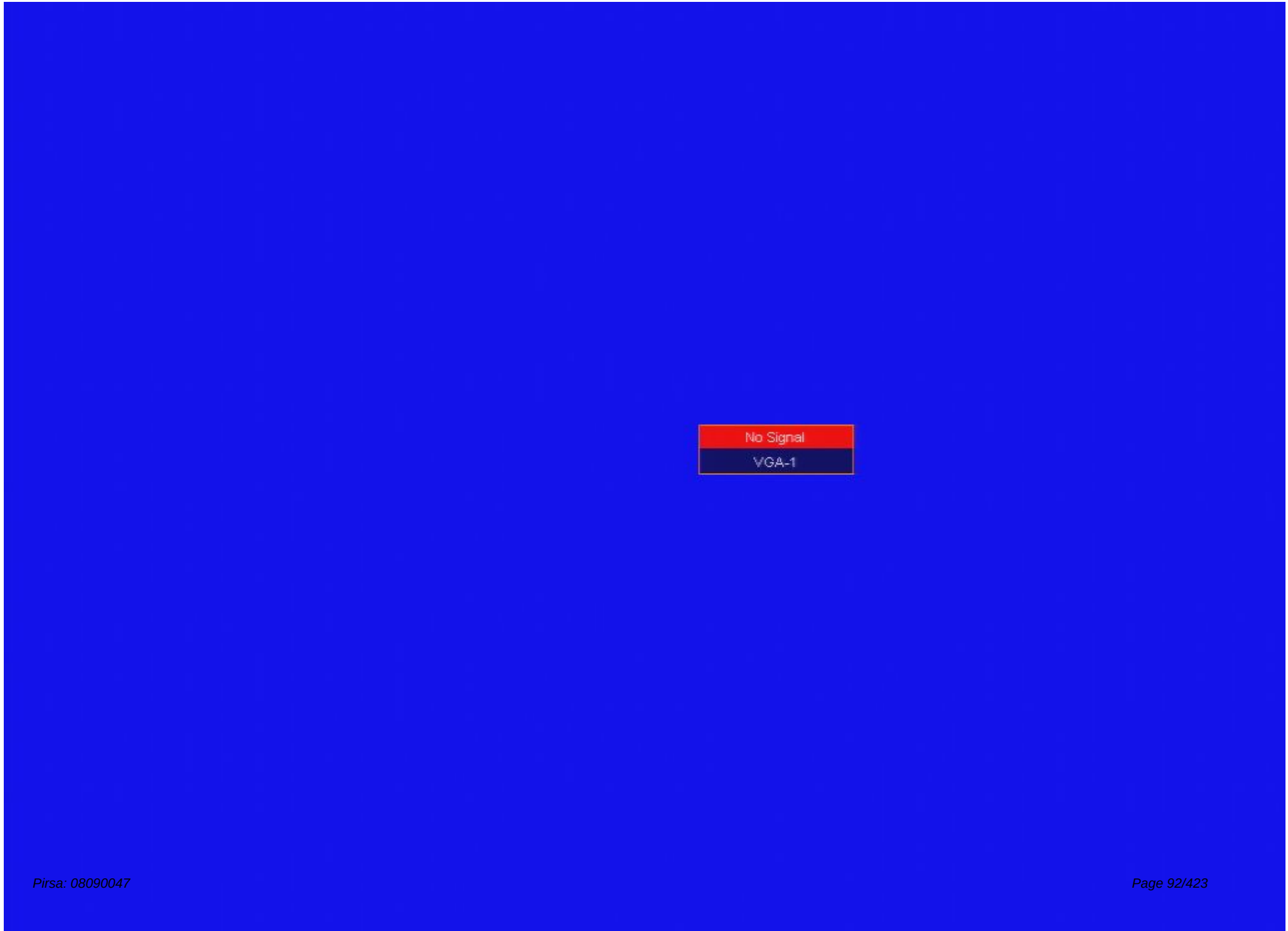

No Signal
VGA-1

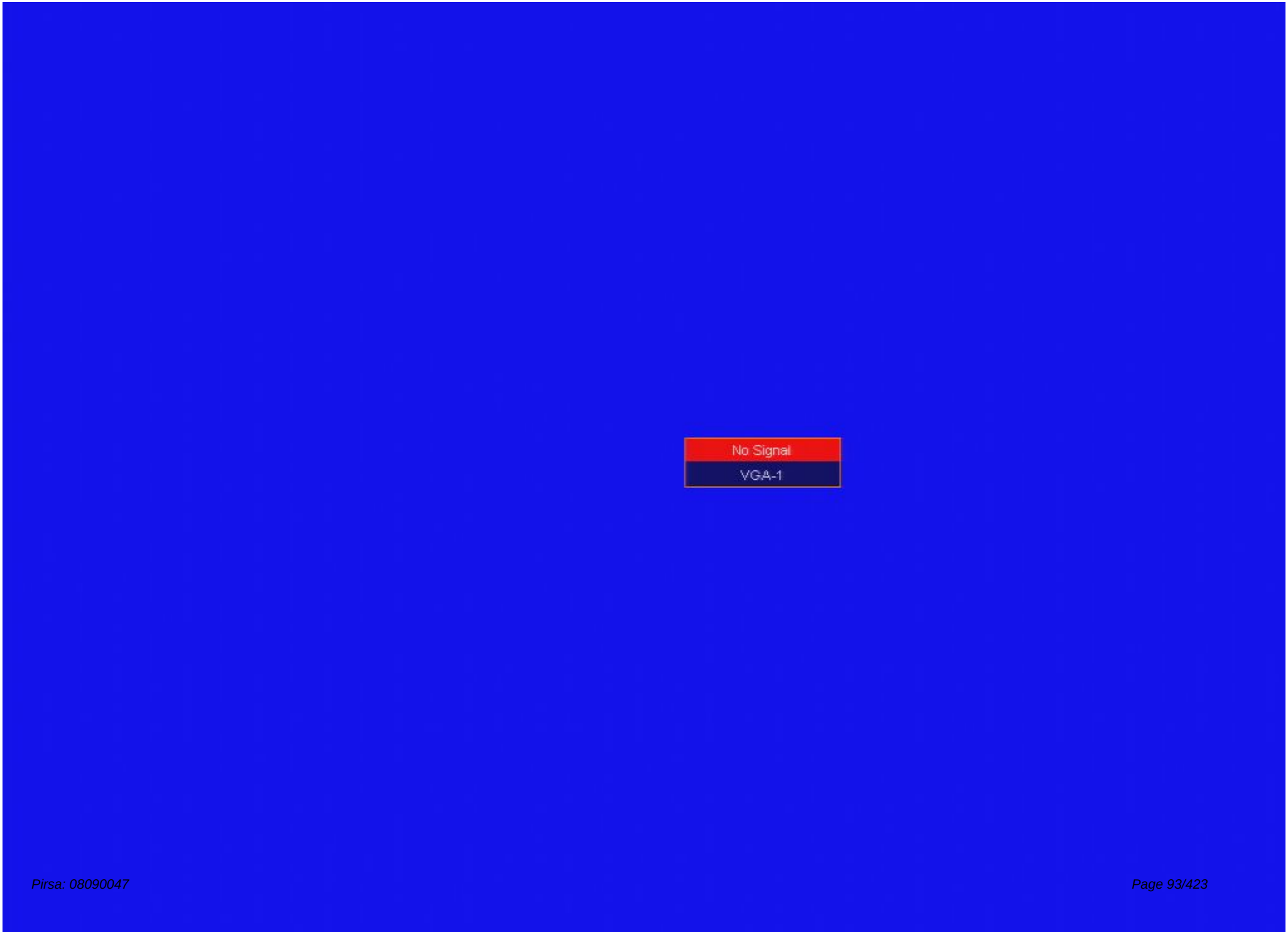

No Signal
VGA-1

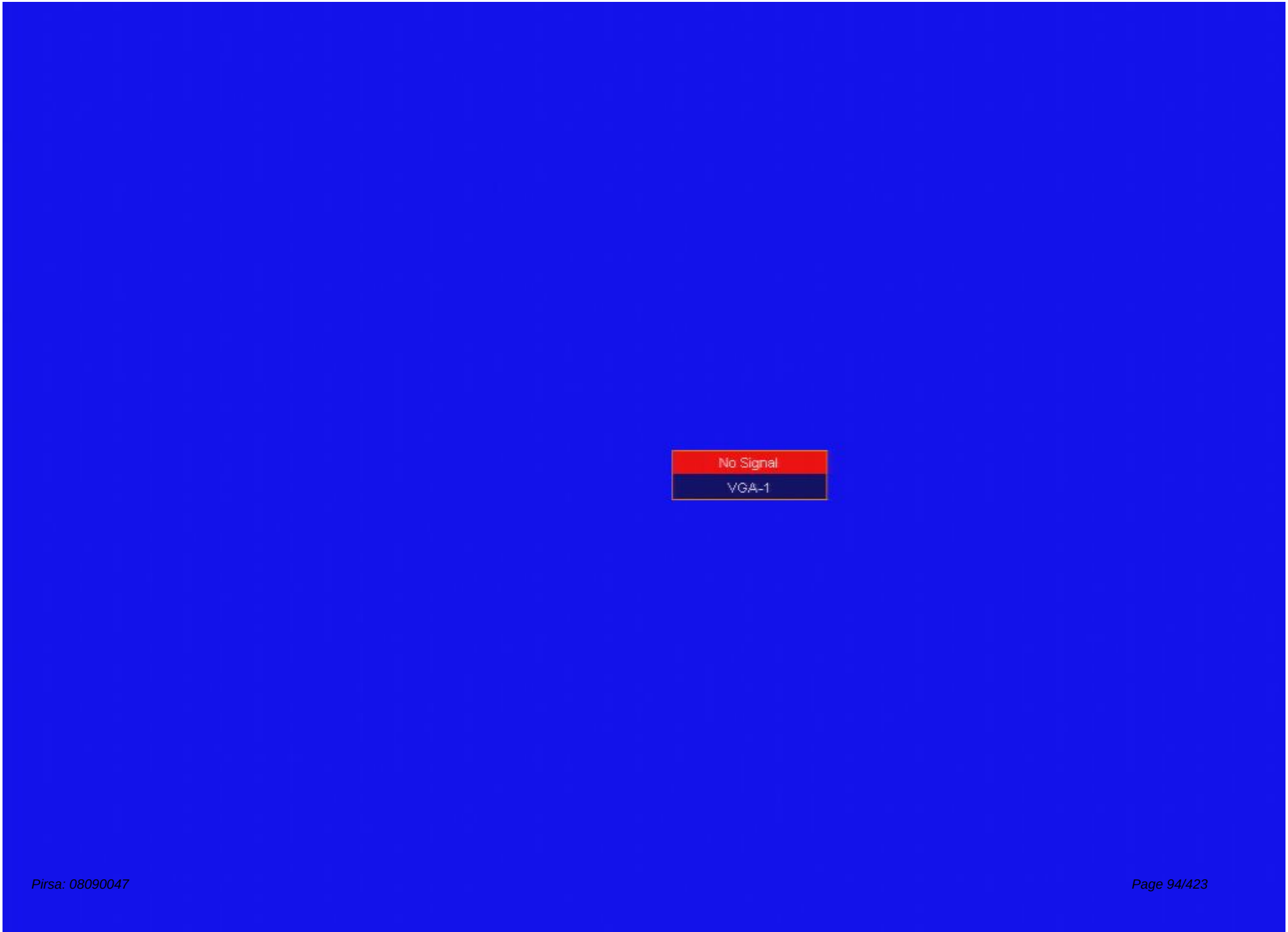

No Signal
VGA-1

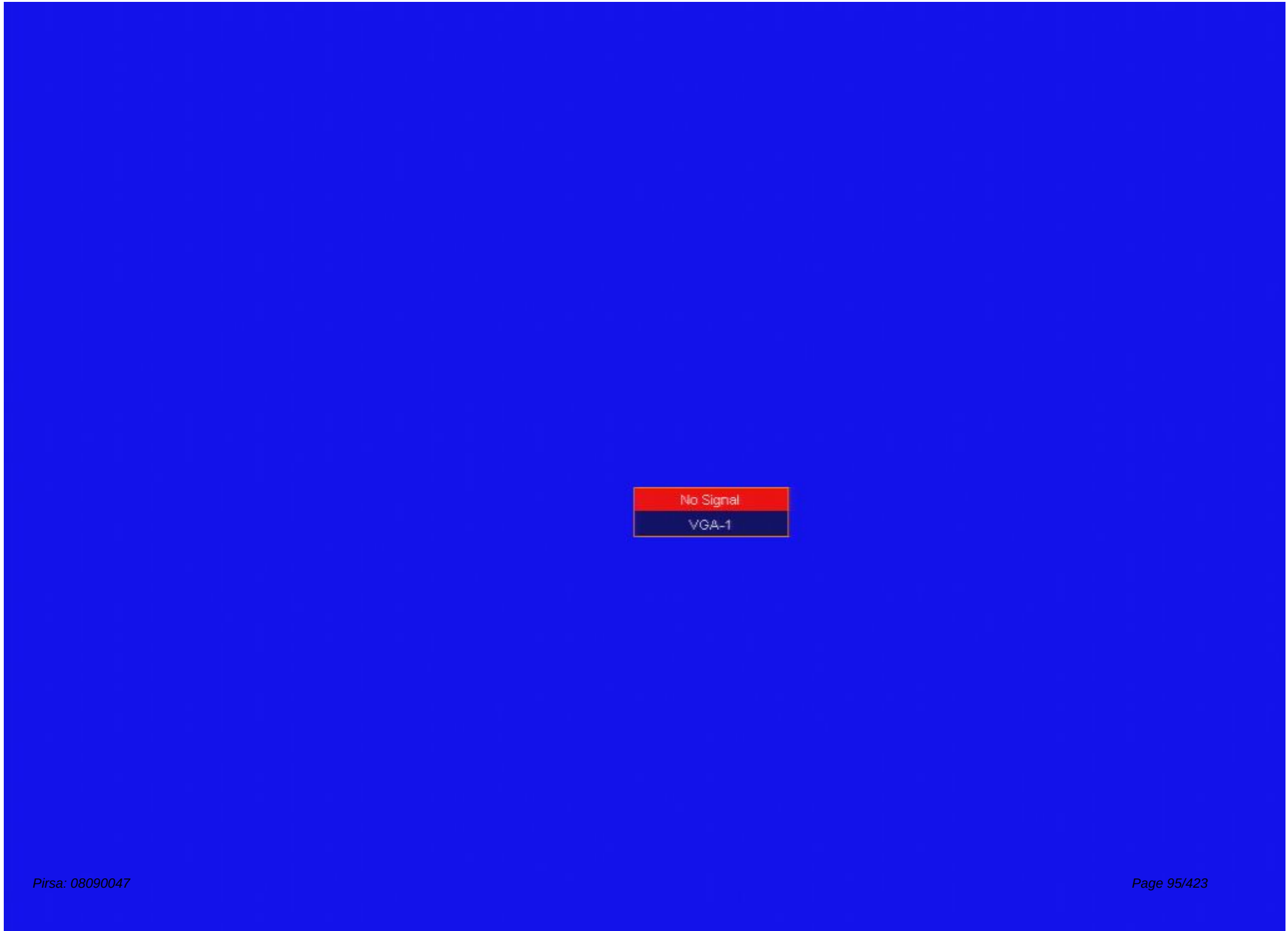

No Signal
VGA-1

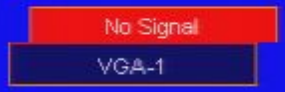

No Signal
VGA-1

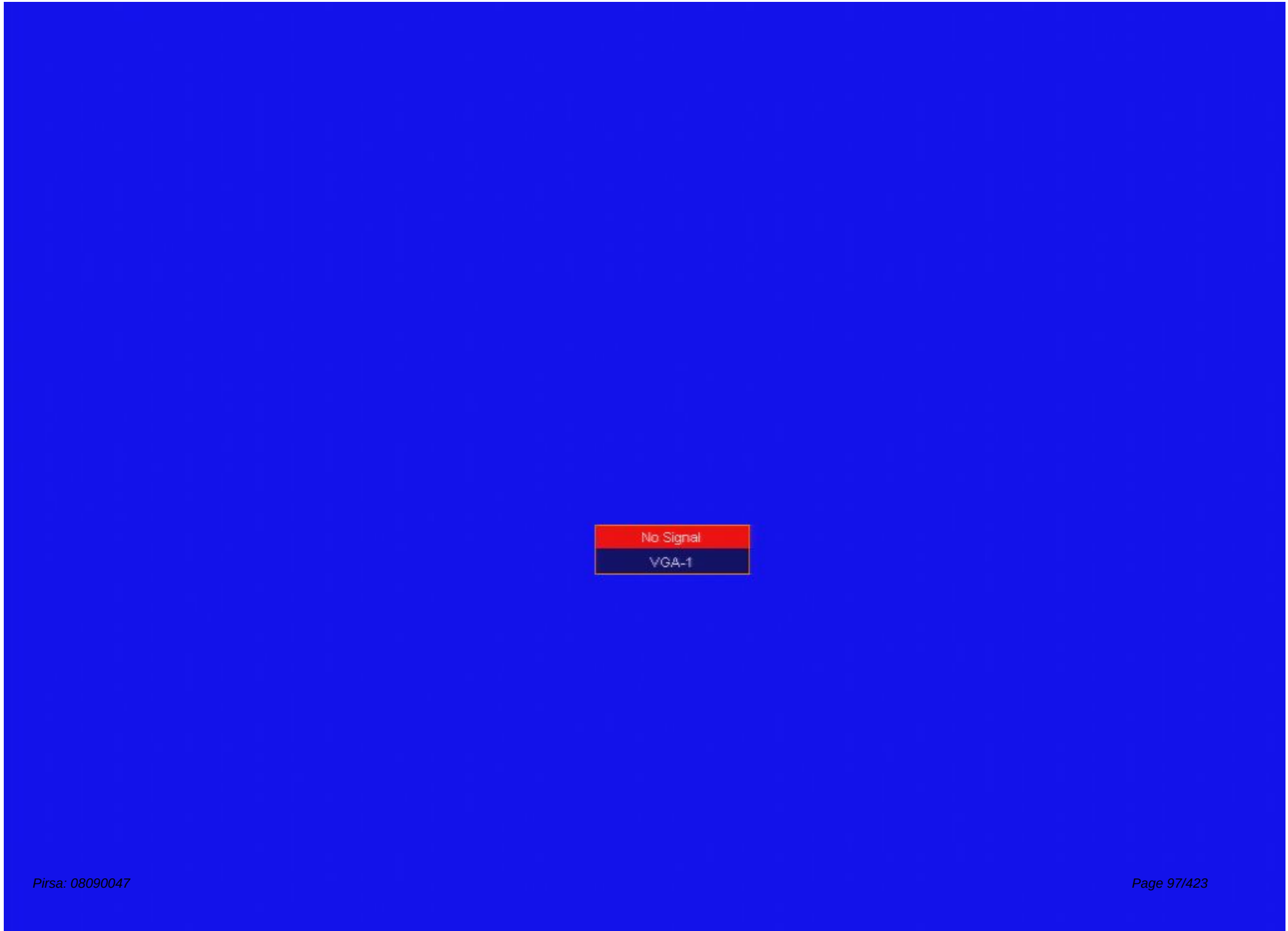

No Signal
VGA-1

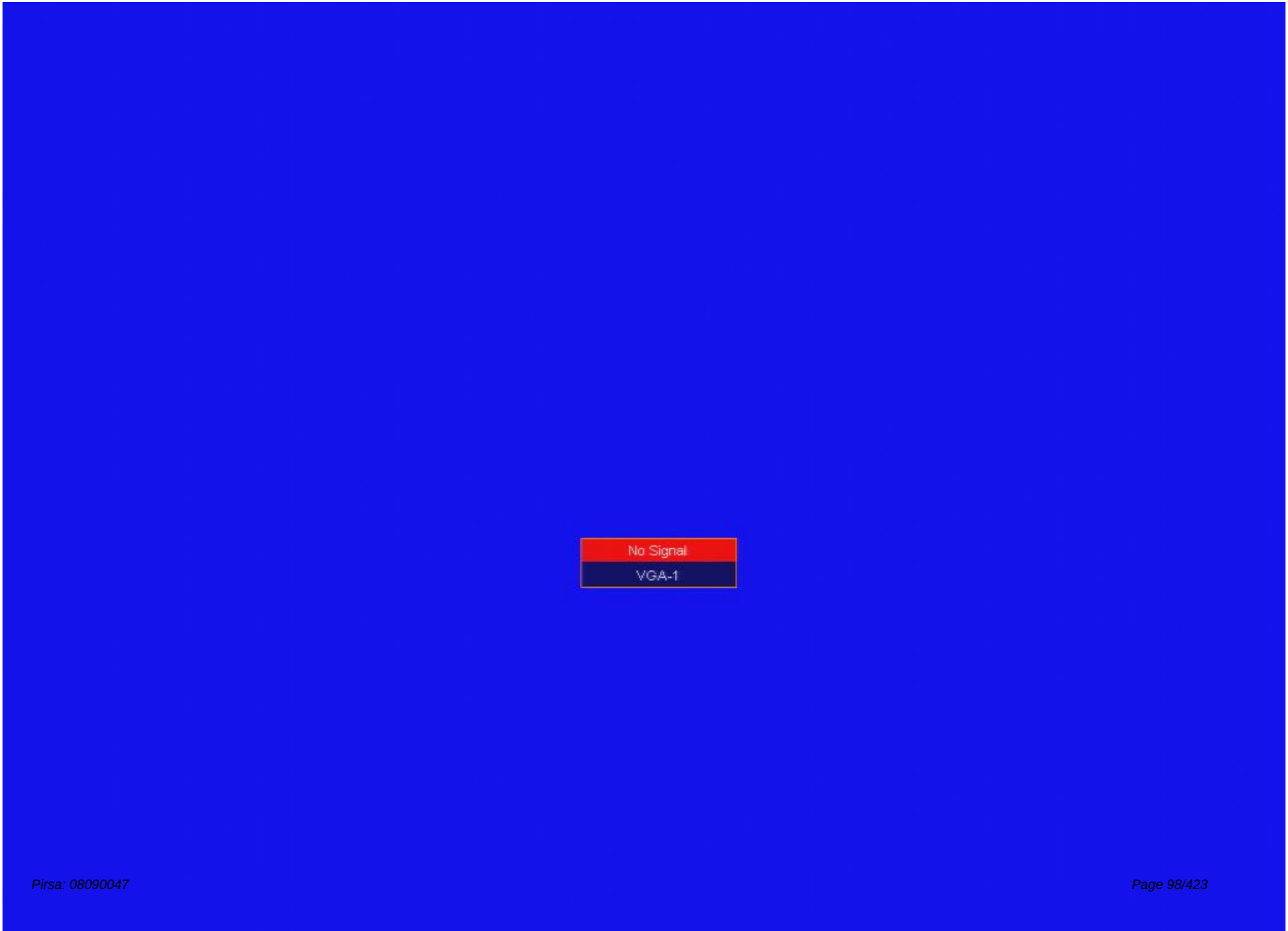

No Signal
VGA-1

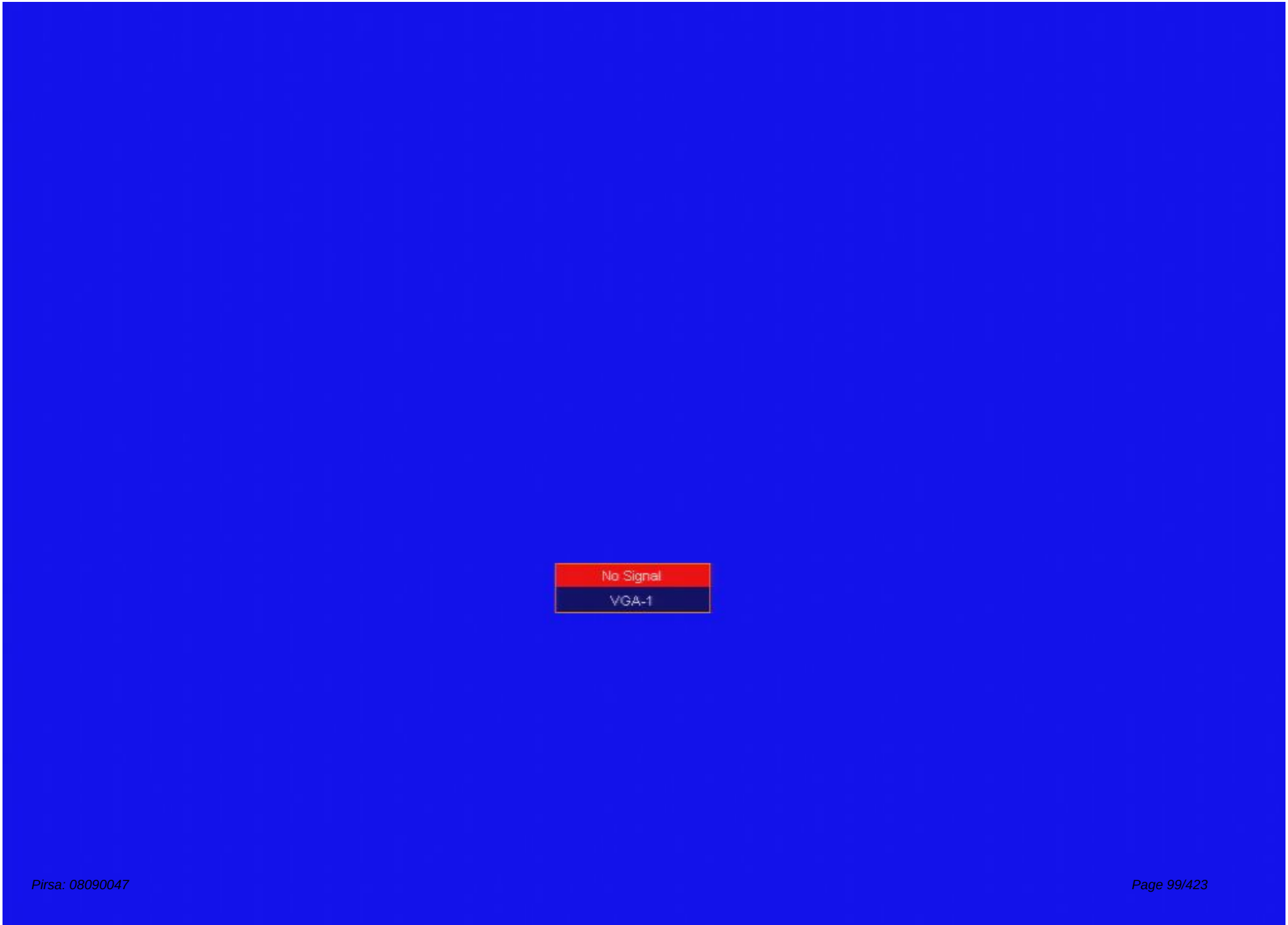

No Signal
VGA-1

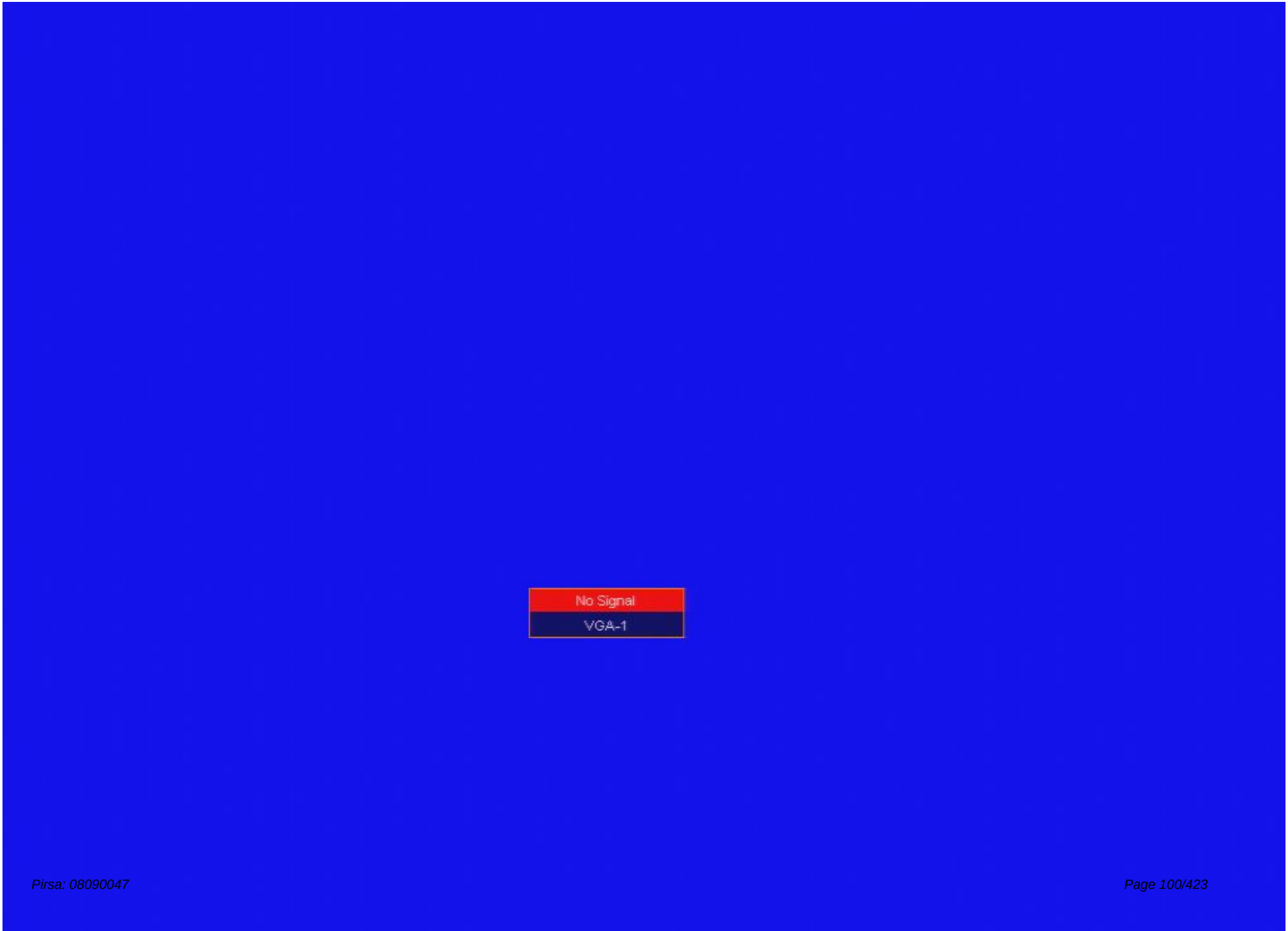

No Signal
VGA-1

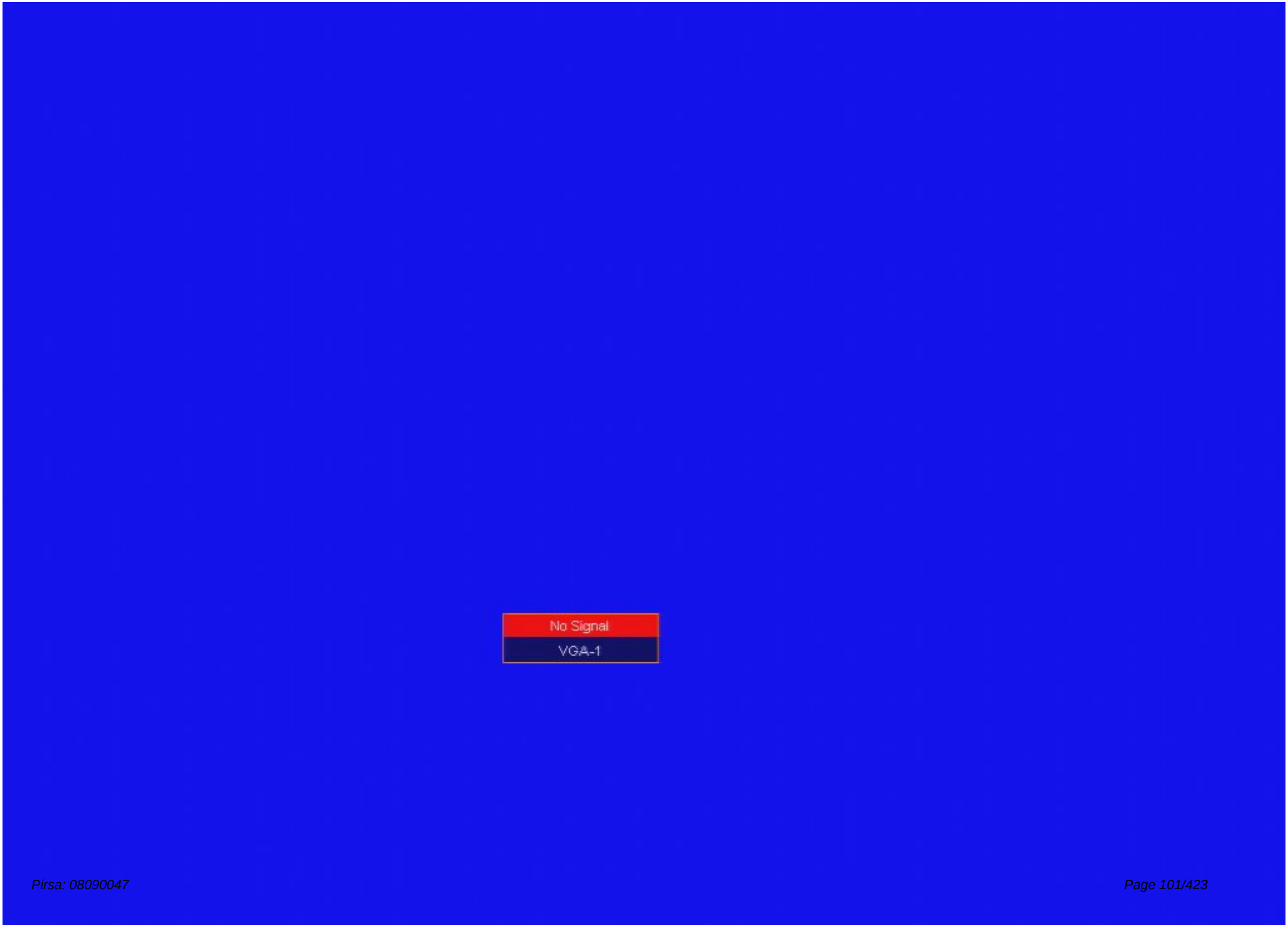

No Signal
VGA-1

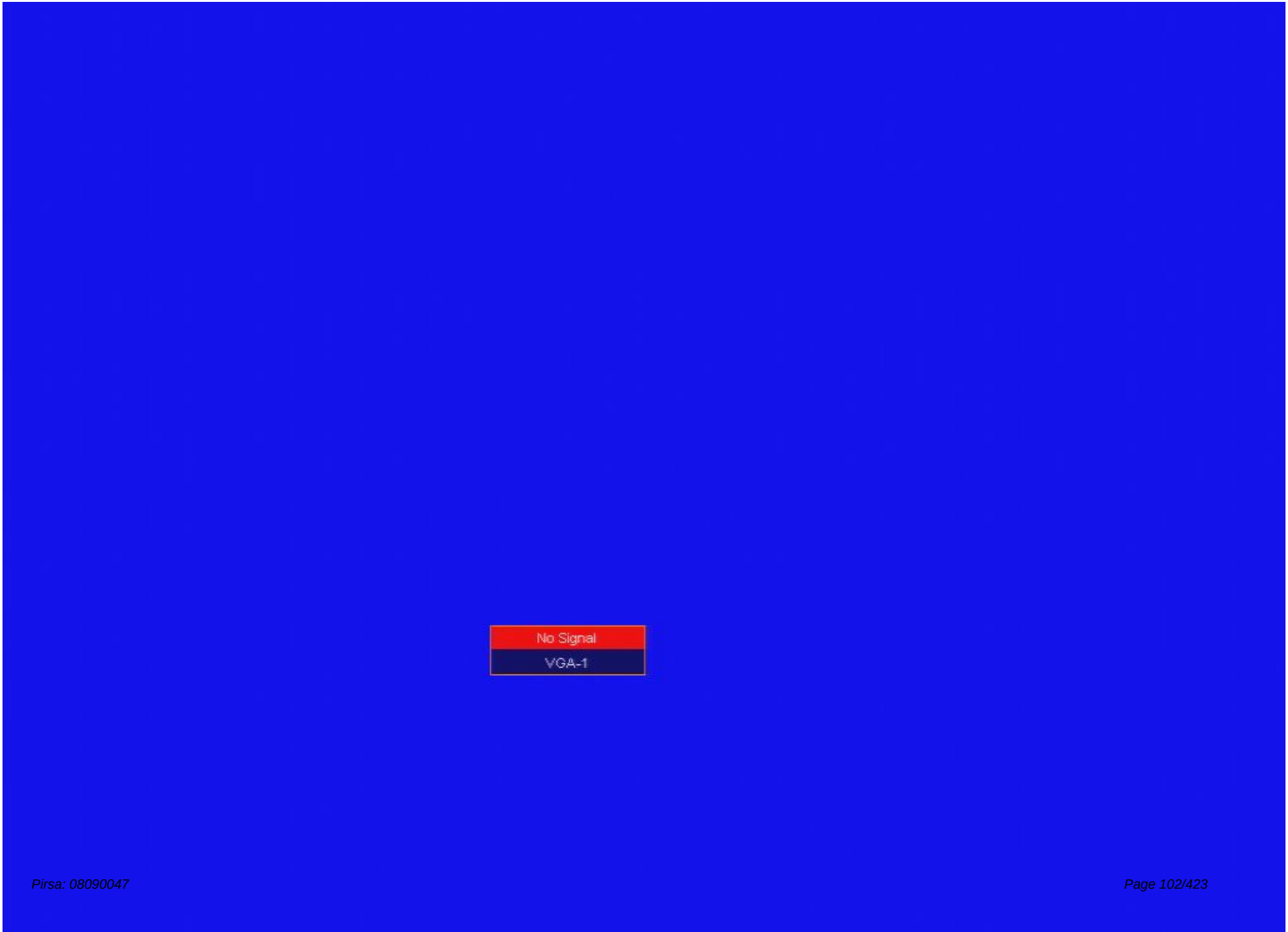

No Signal
VGA-1

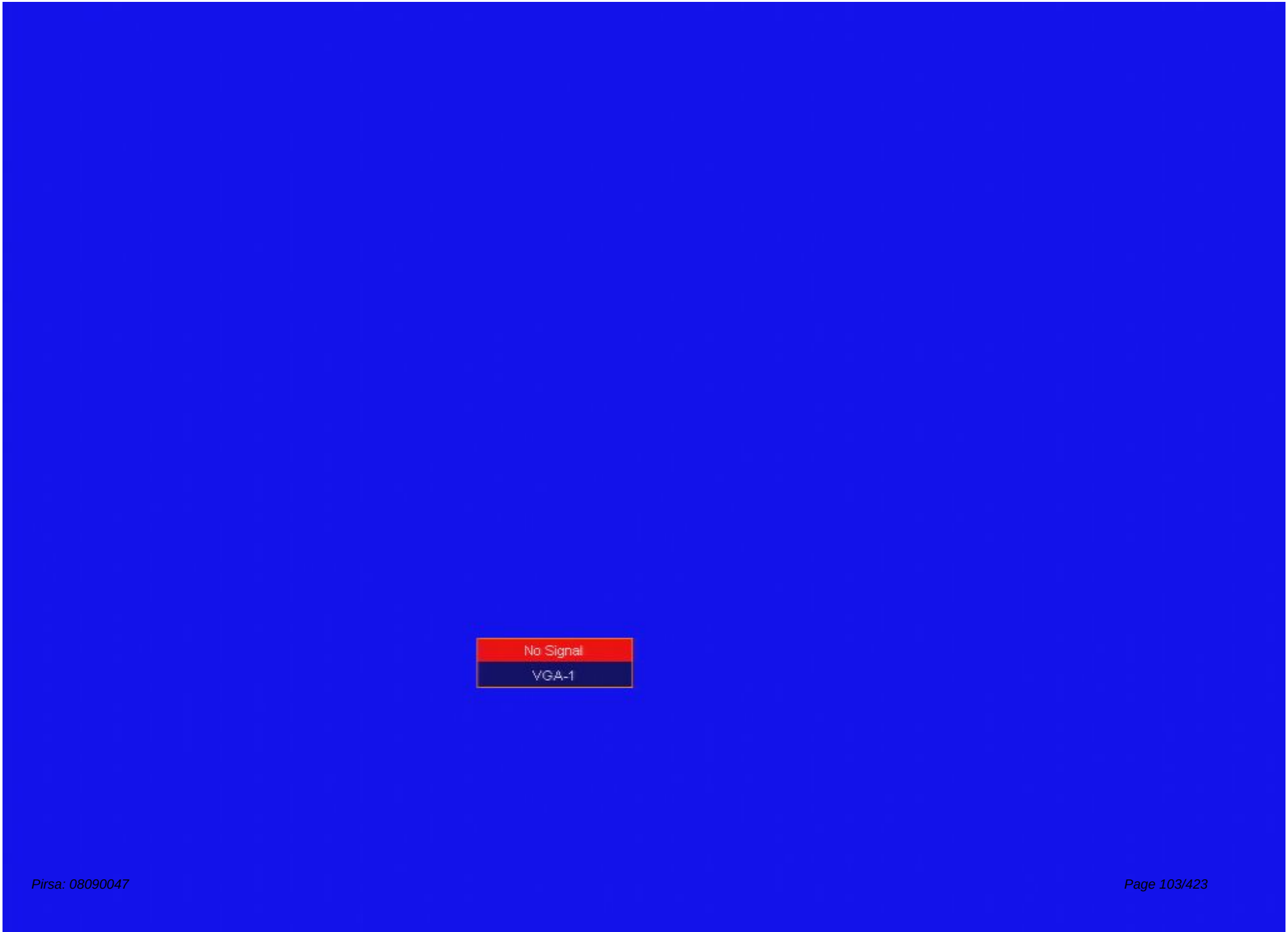

No Signal
VGA-1

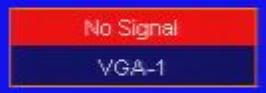

No Signal
VGA-1

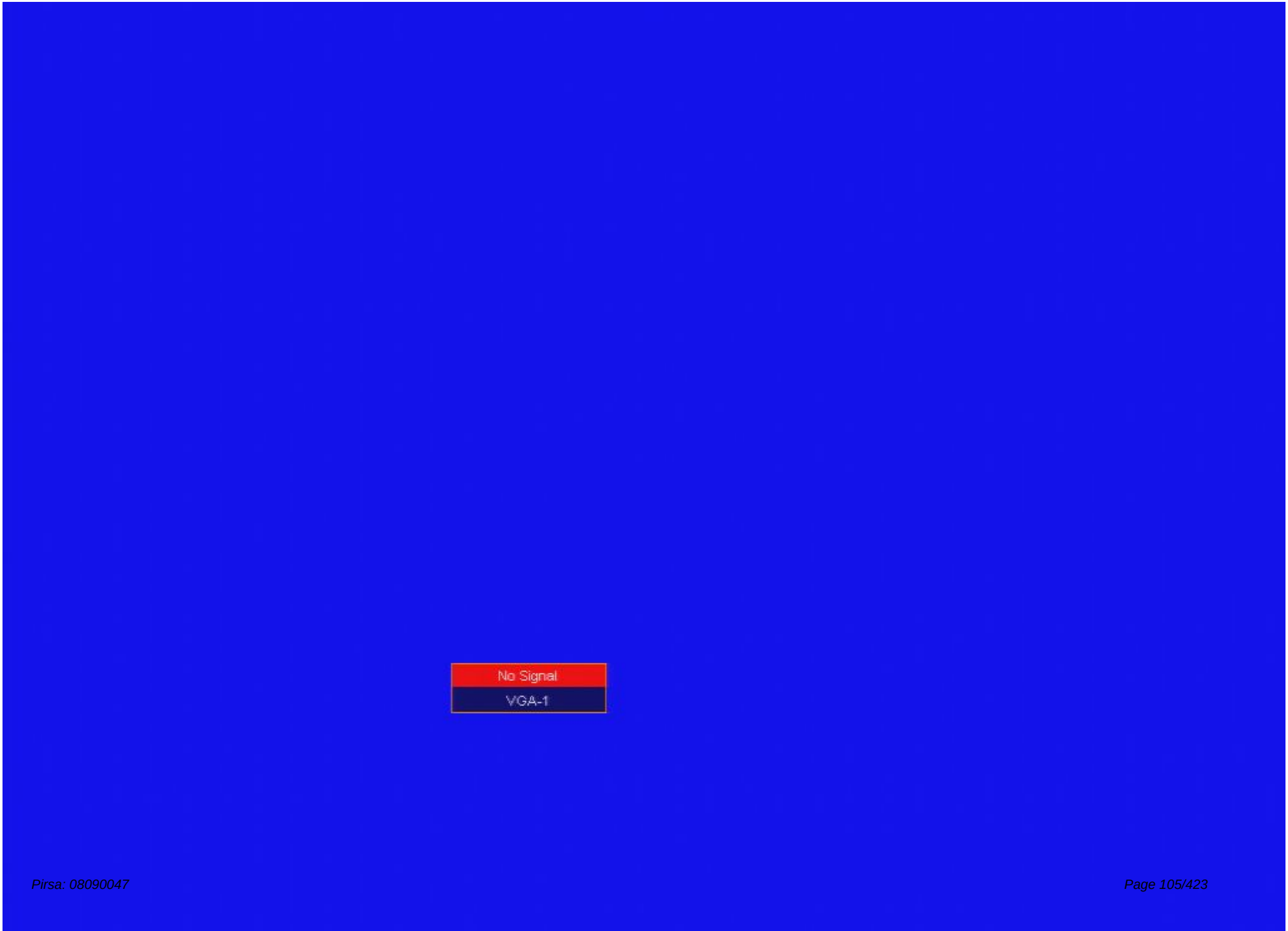

No Signal
VGA-1

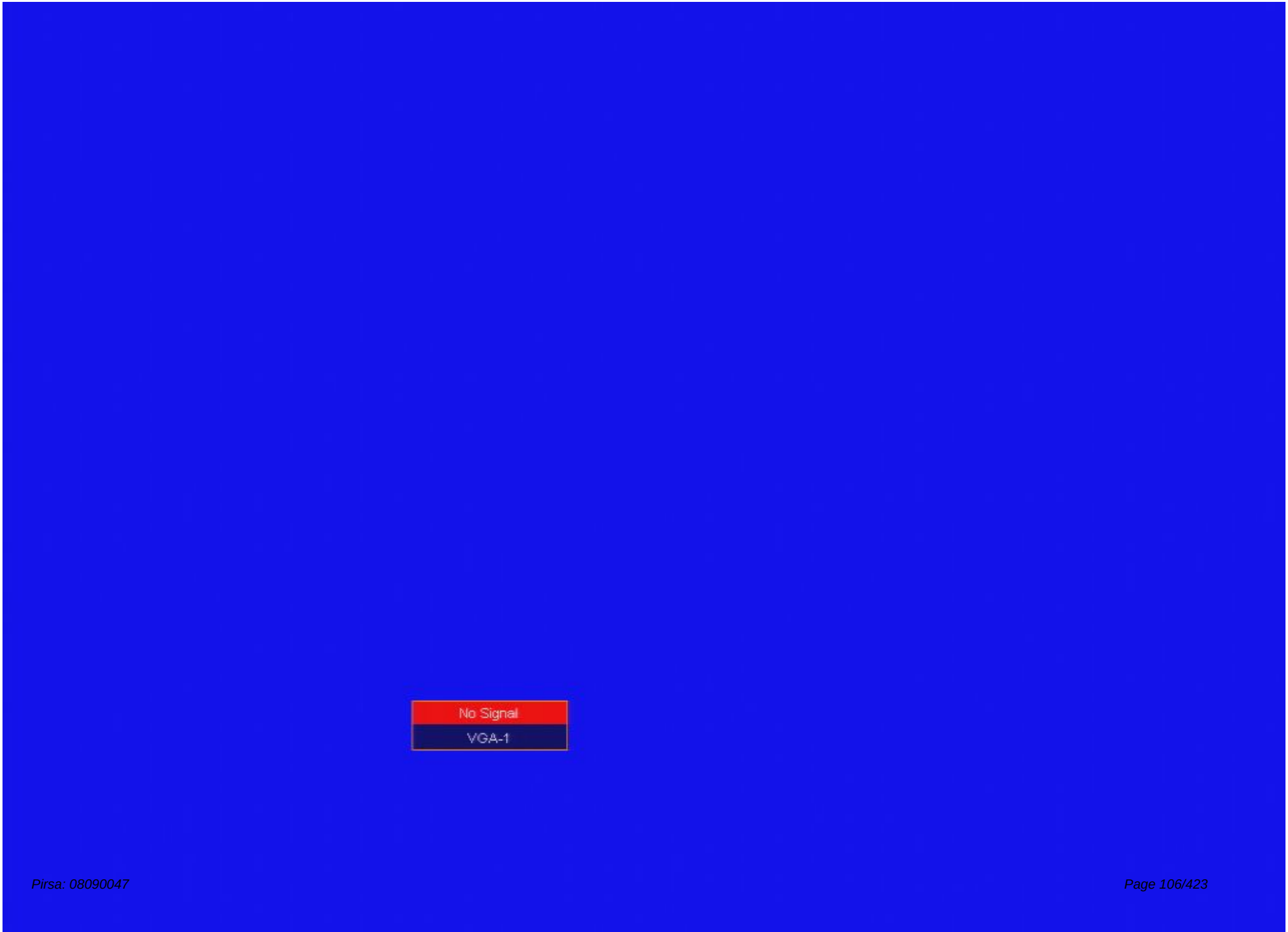

No Signal
VGA-1

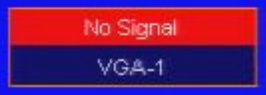

No Signal
VGA-1

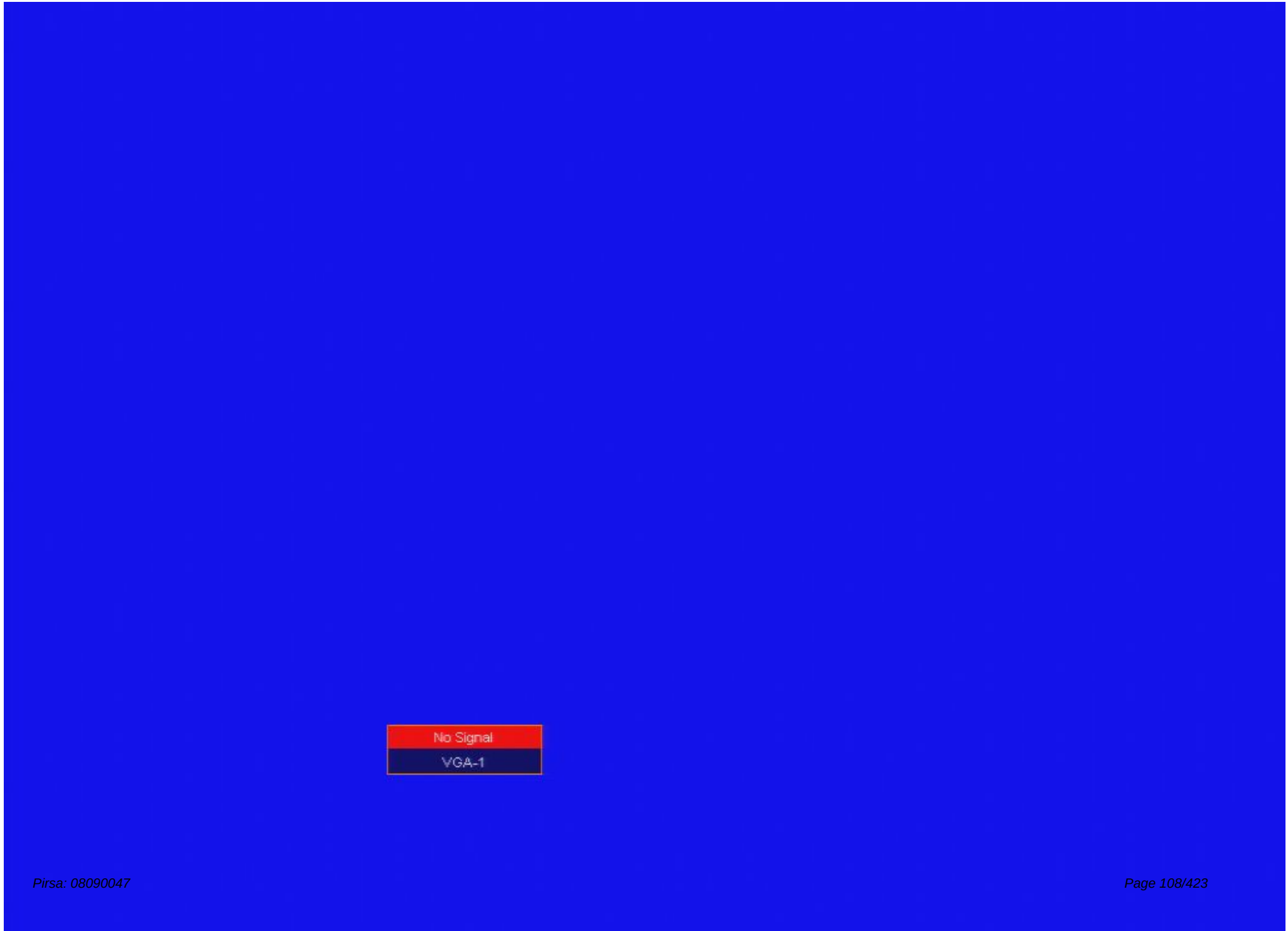

No Signal
VGA-1


No Signal
VGA-1

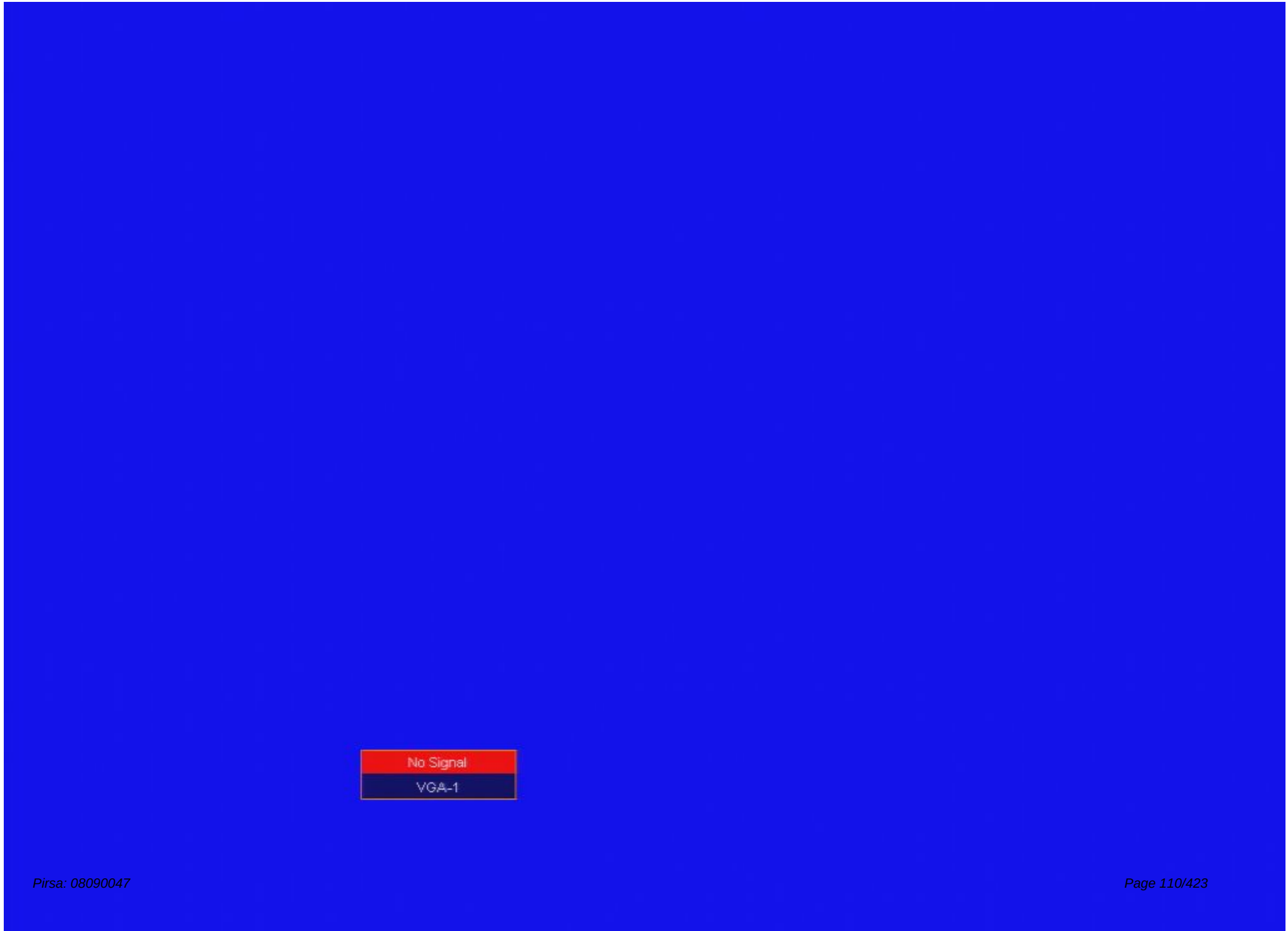

No Signal
VGA-1


No Signal
VGA-1

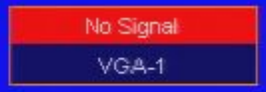

No Signal
VGA-1

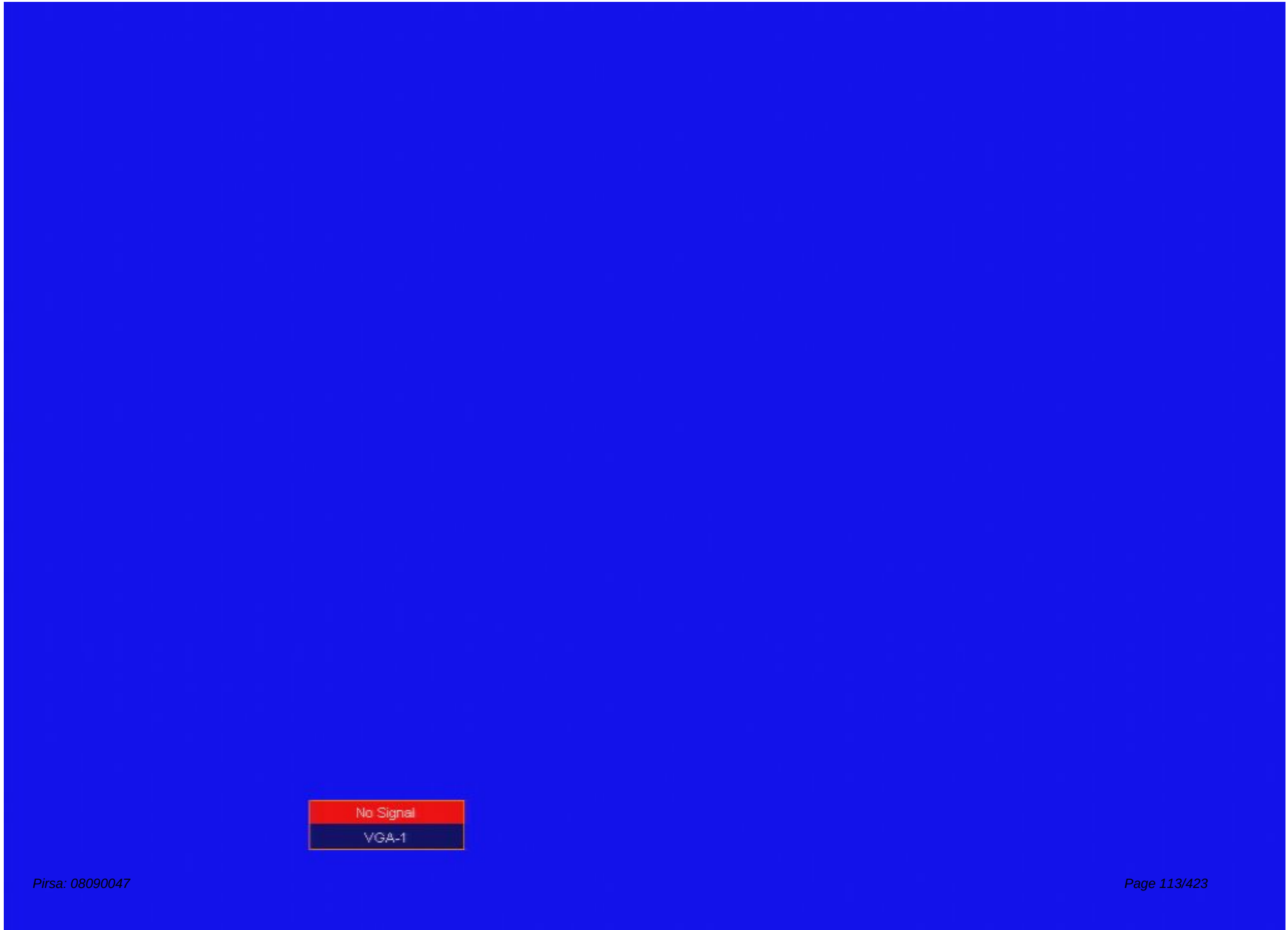

No Signal
VGA-1

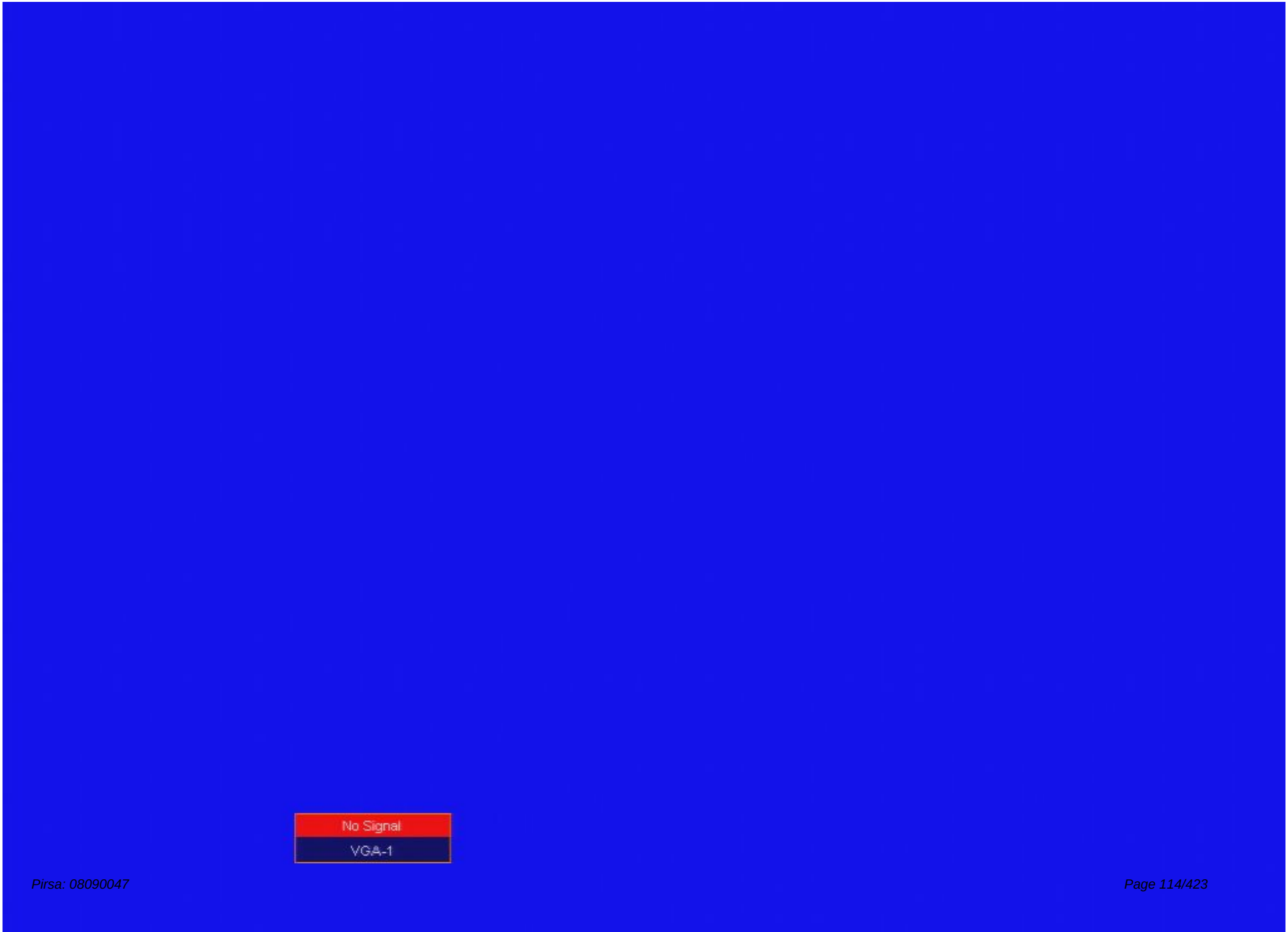

No Signal
VGA-1


No Signal
VGA-1

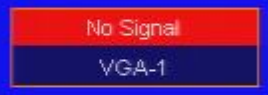

No Signal
VGA-1

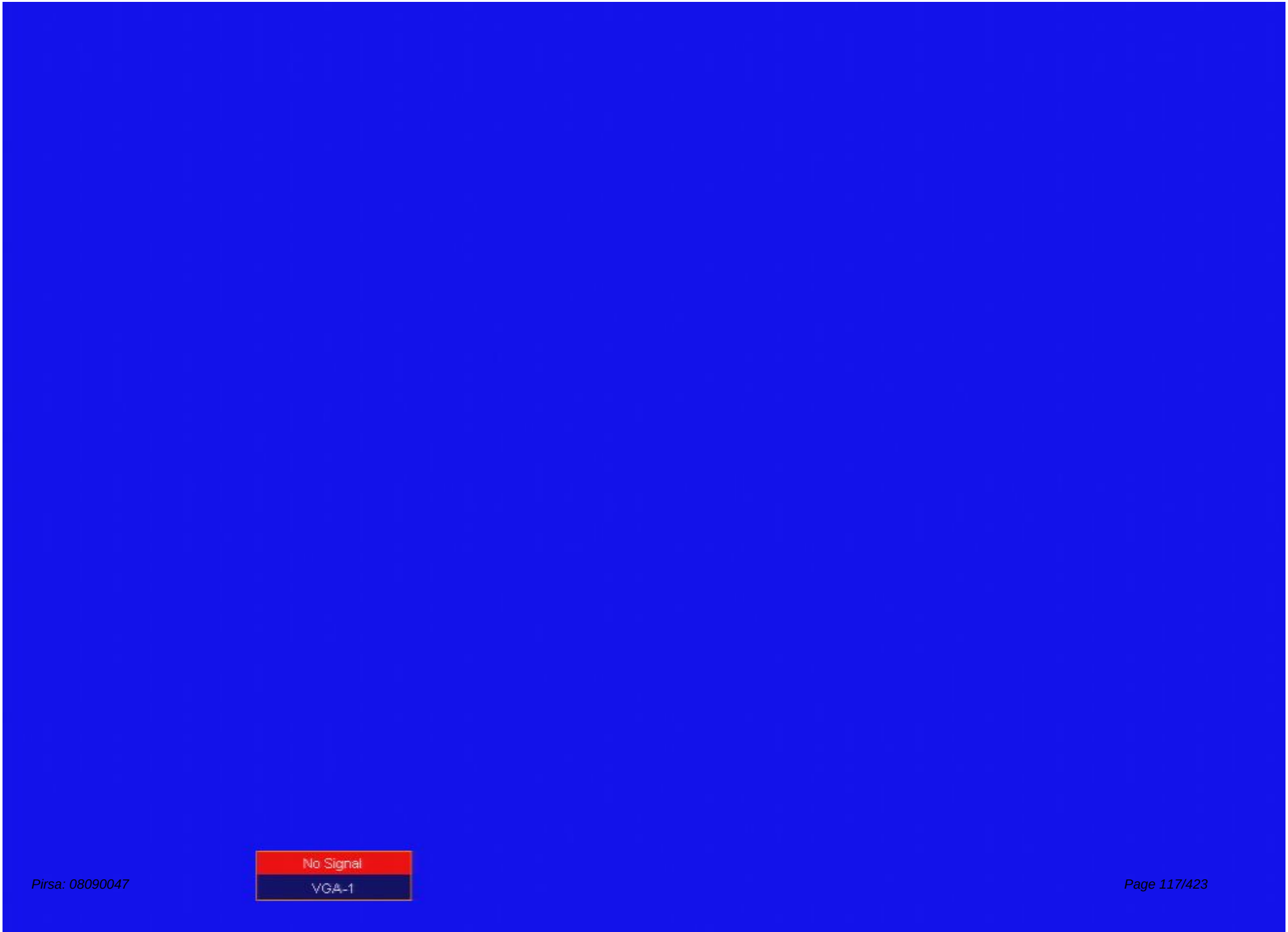

No Signal
VGA-1

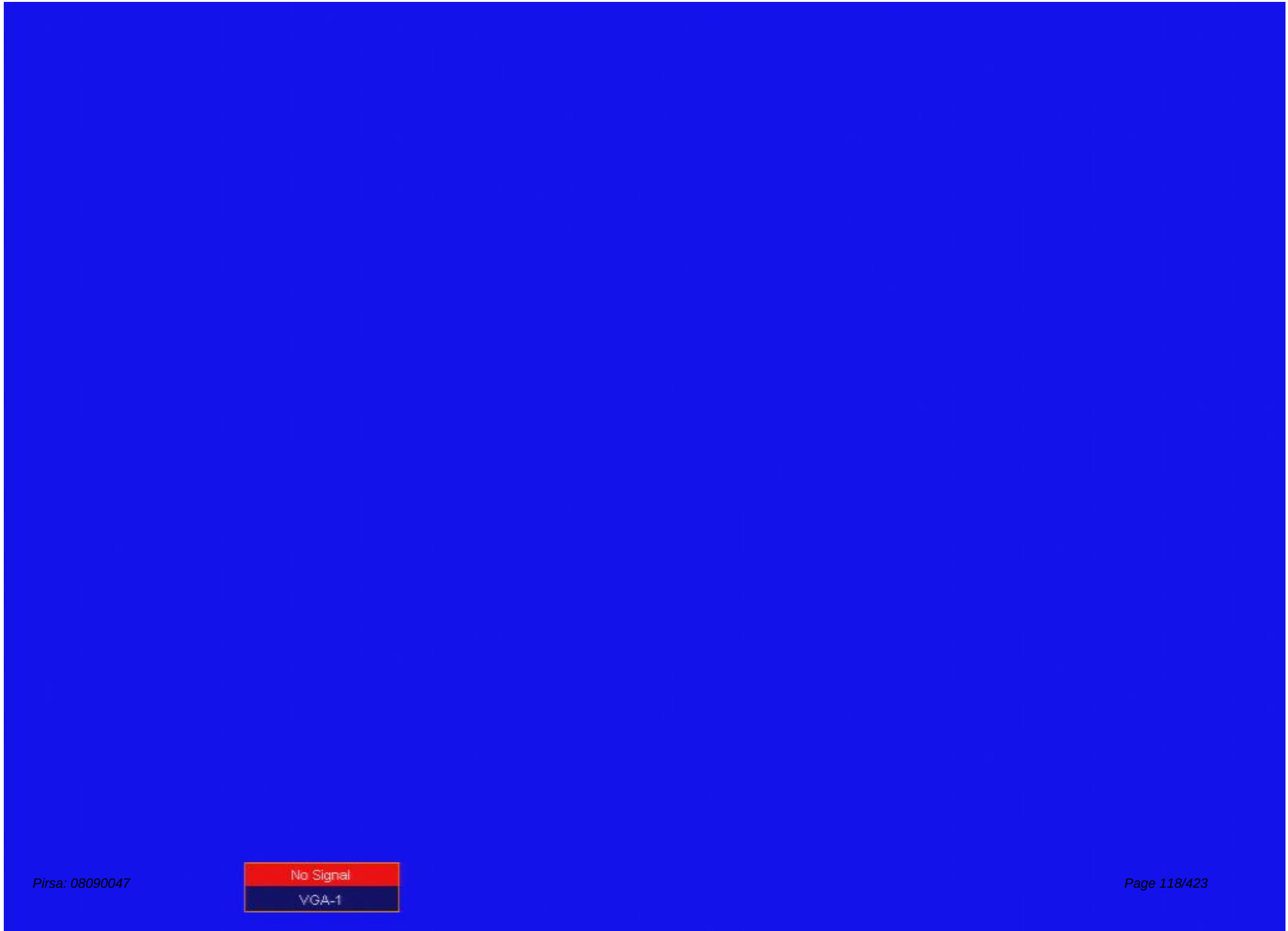

No Signal
VGA-1

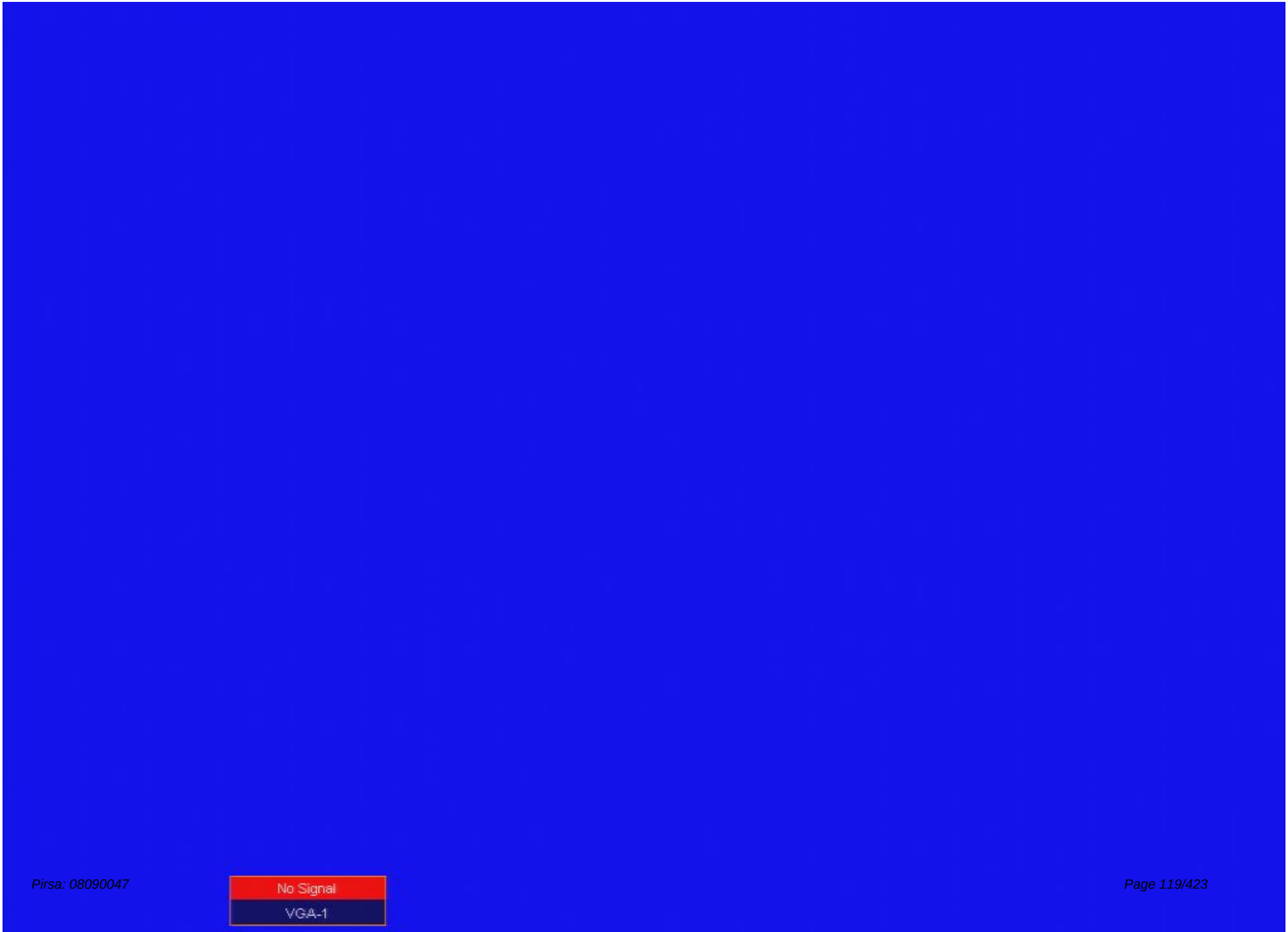

No Signal
VGA-1


No Signal
VGA-1

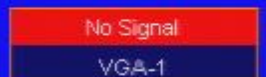

No Signal
VGA-1


No Signal
VGA-1

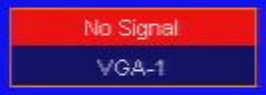

No Signal
VGA-1


No Signal
VGA-1

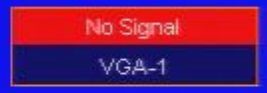

No Signal

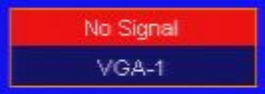

No Signal
VGA-1


No Signal
VGA-1

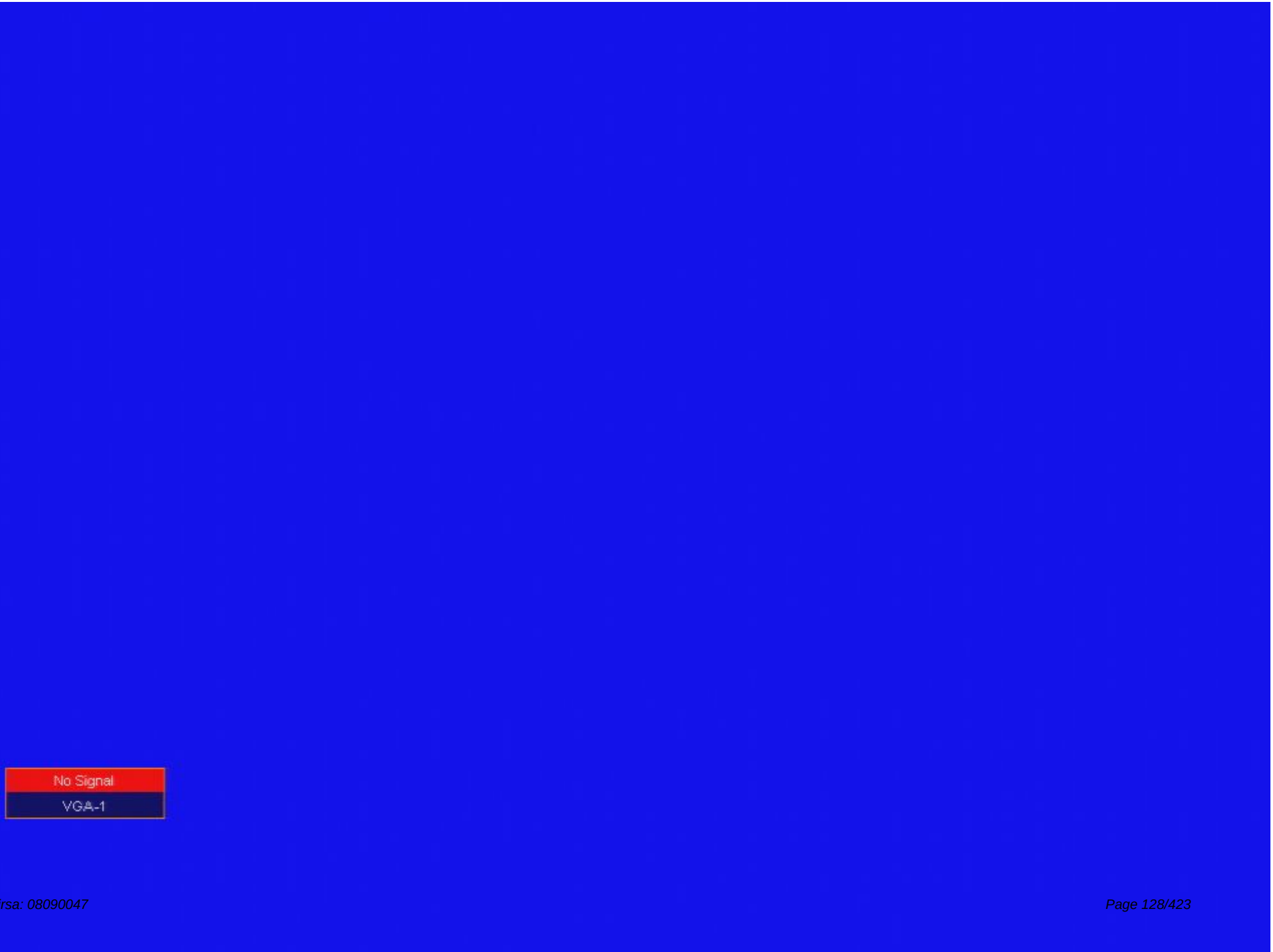

No Signal
VGA-1


No Signal
VGA-1

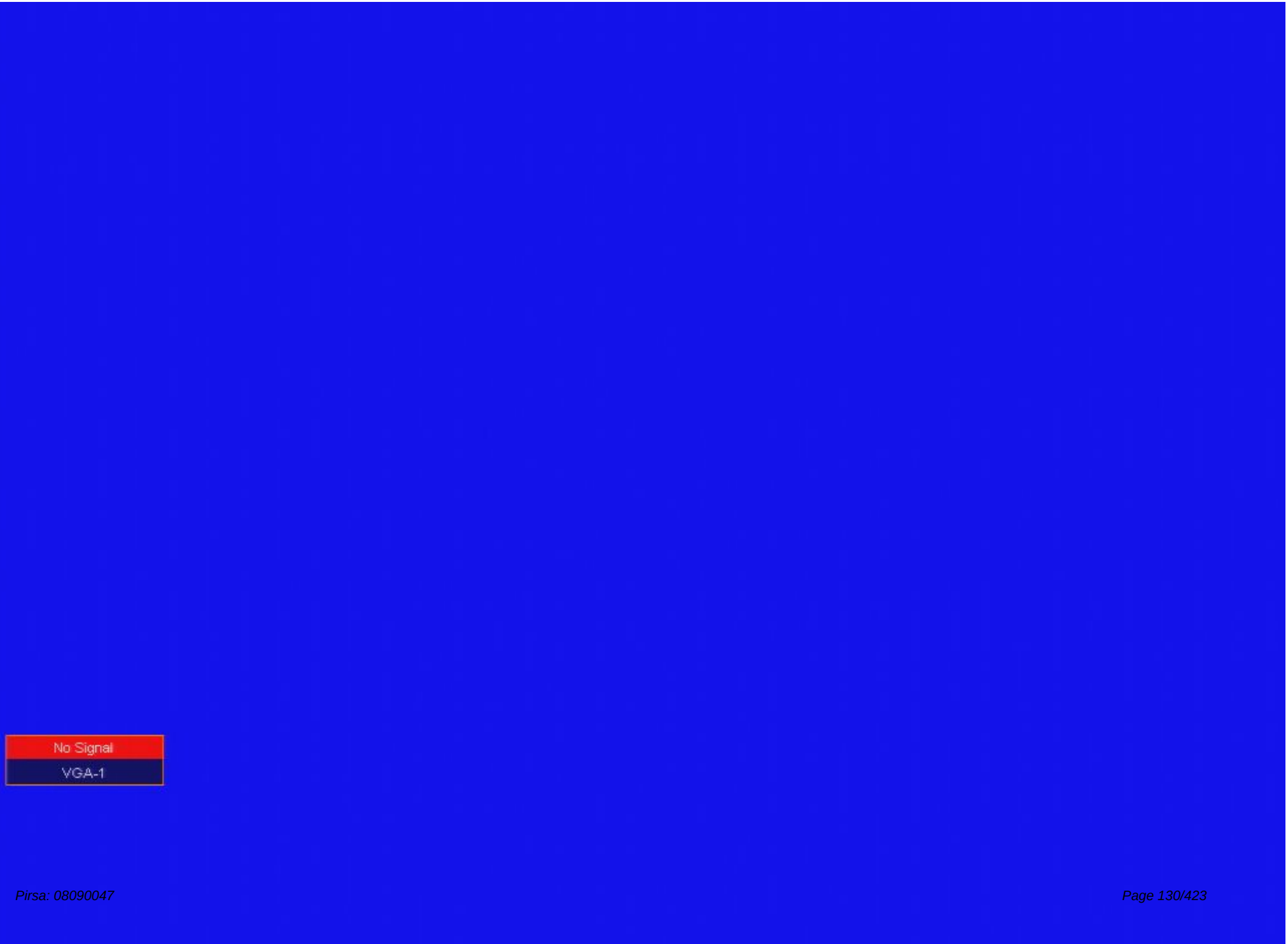

No Signal
VGA-1

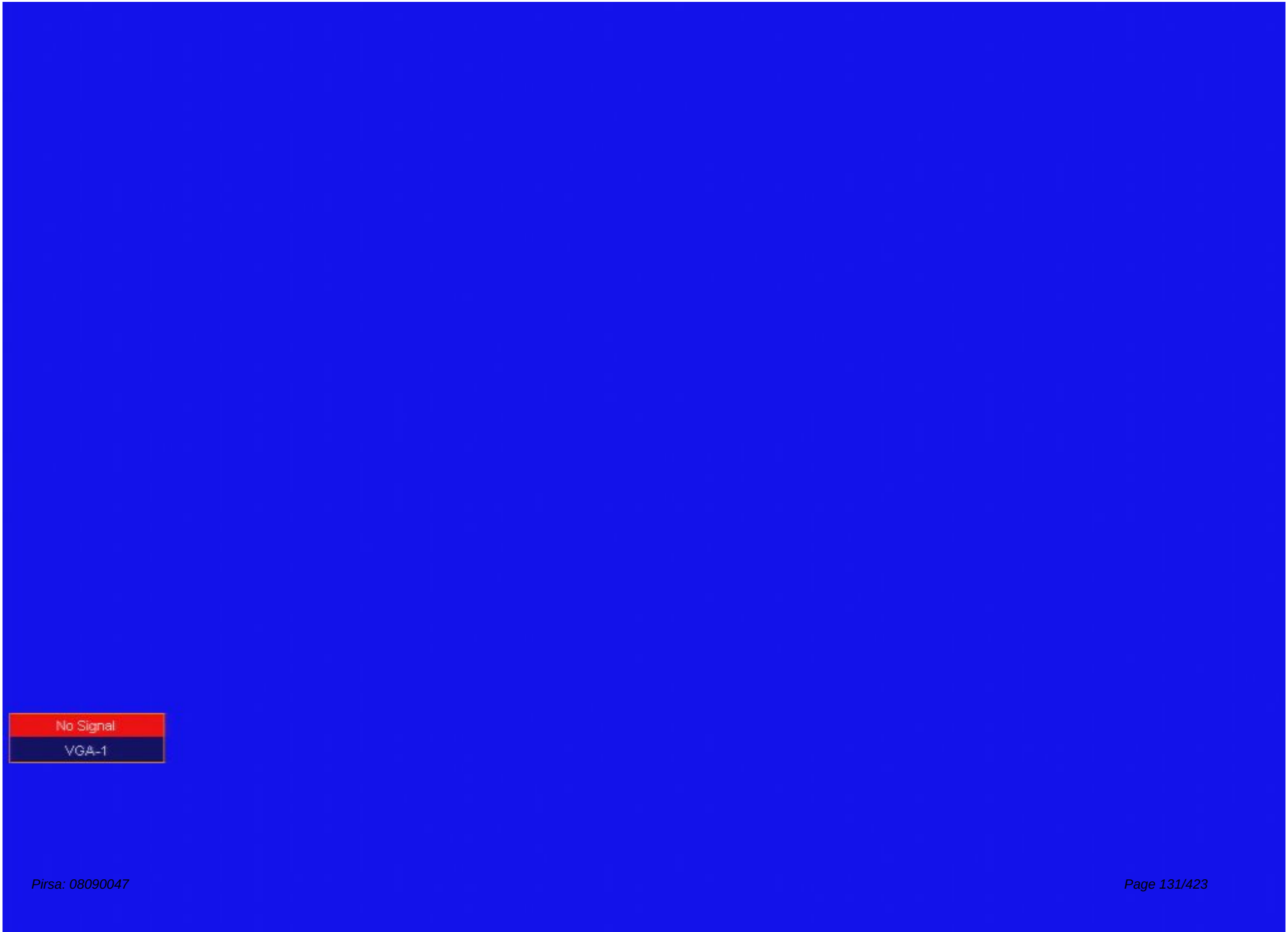

No Signal
VGA-1

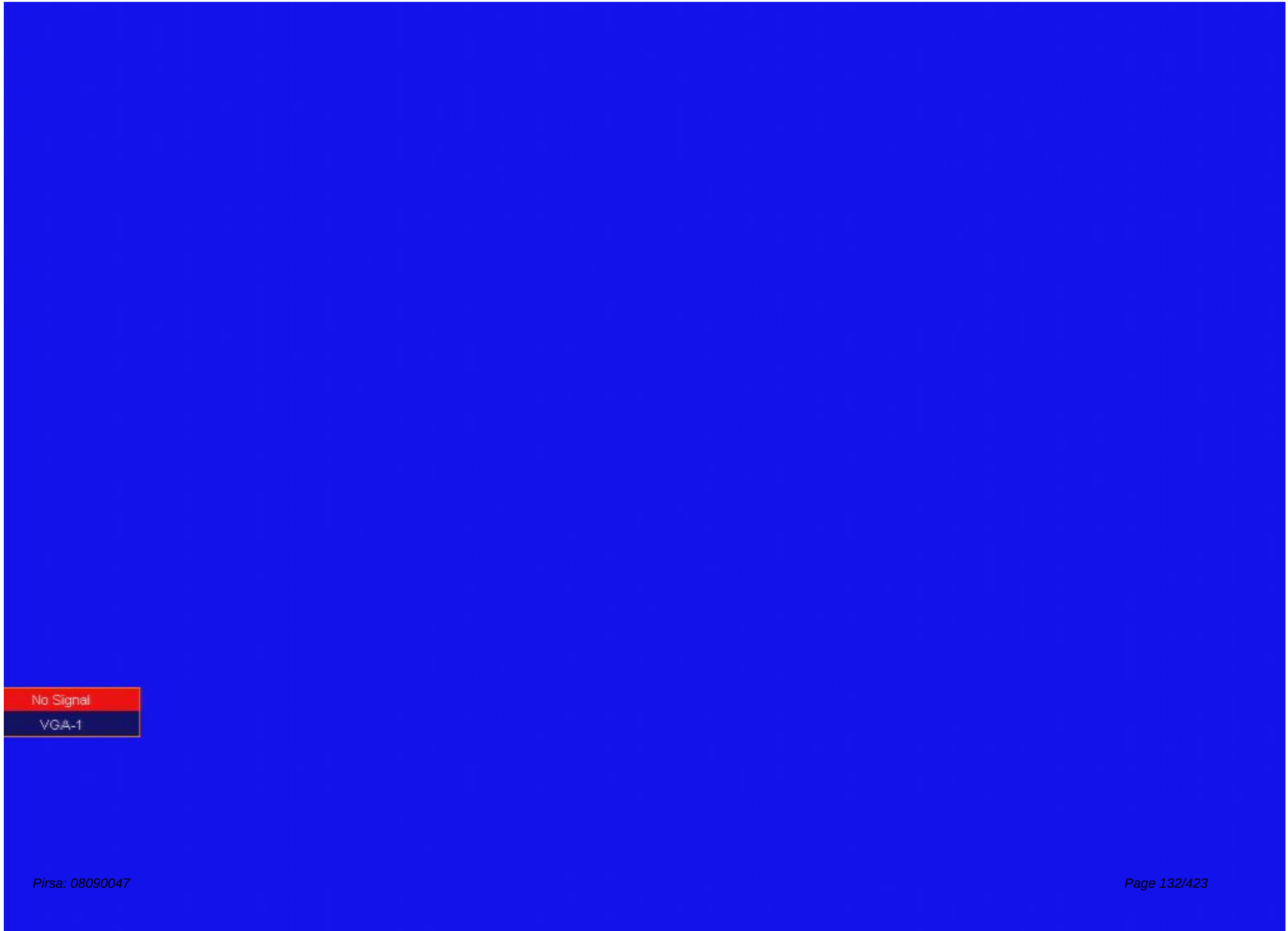

No Signal
VGA-1

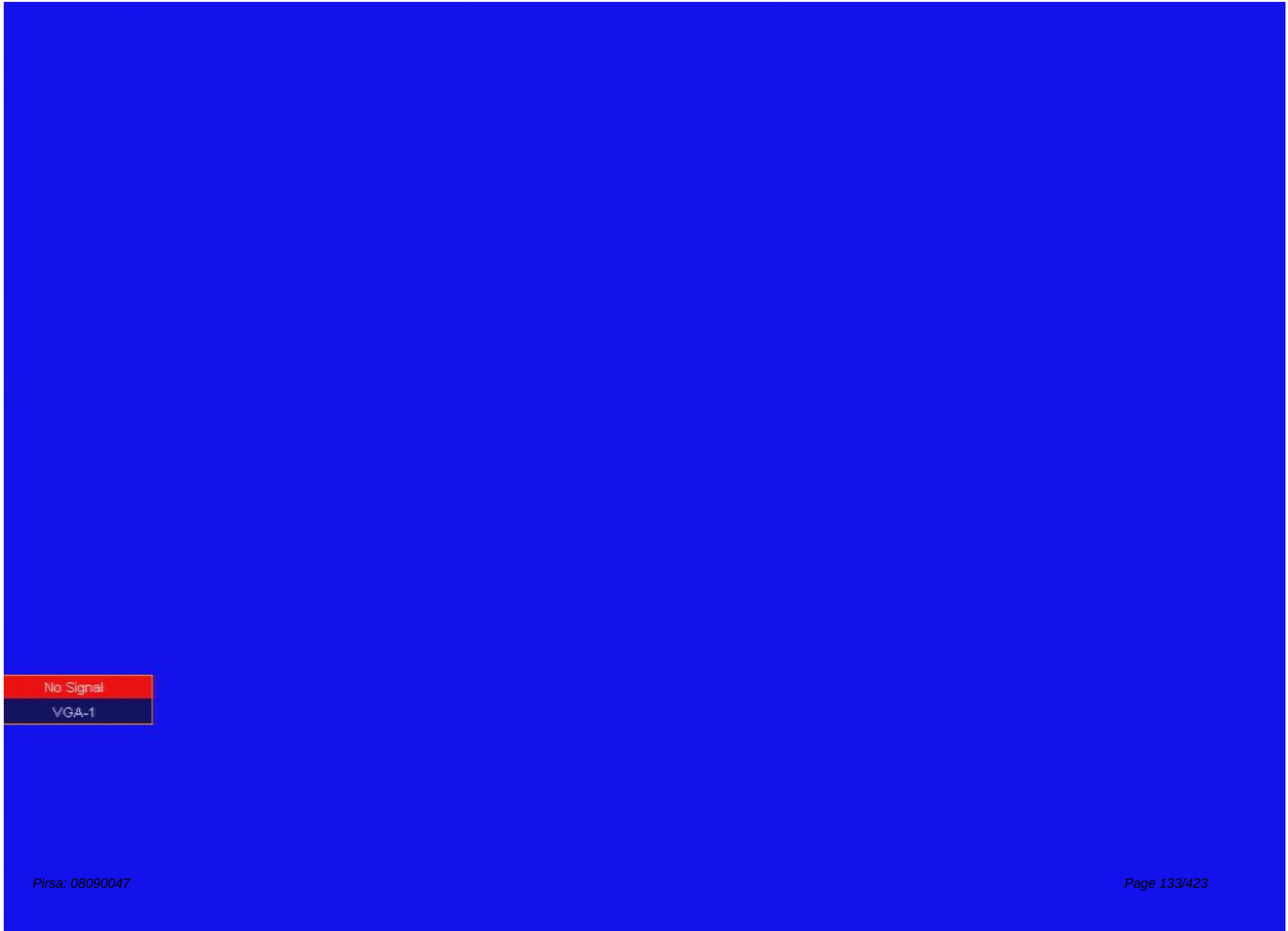

No Signal
VGA-1

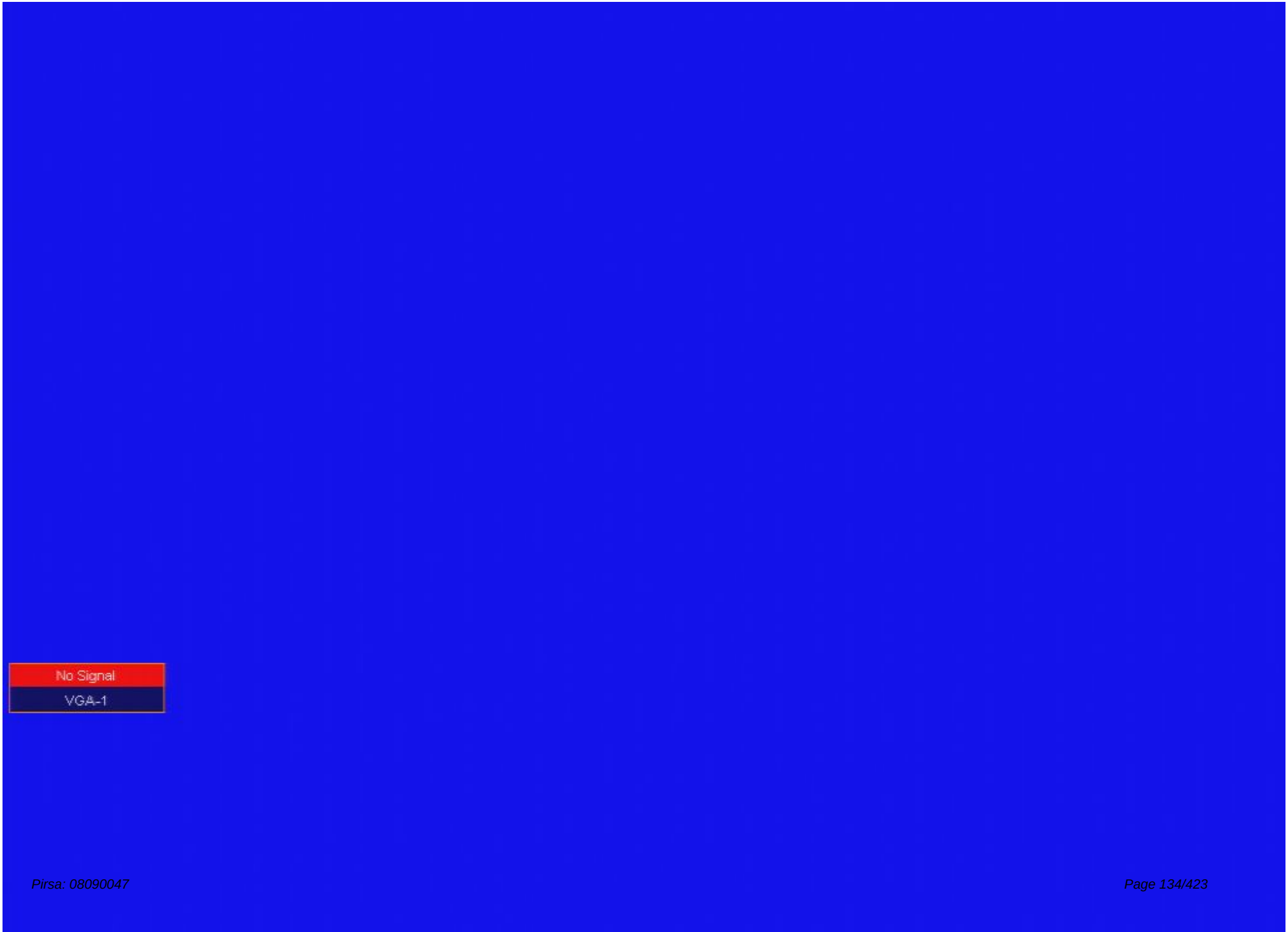

No Signal
VGA-1

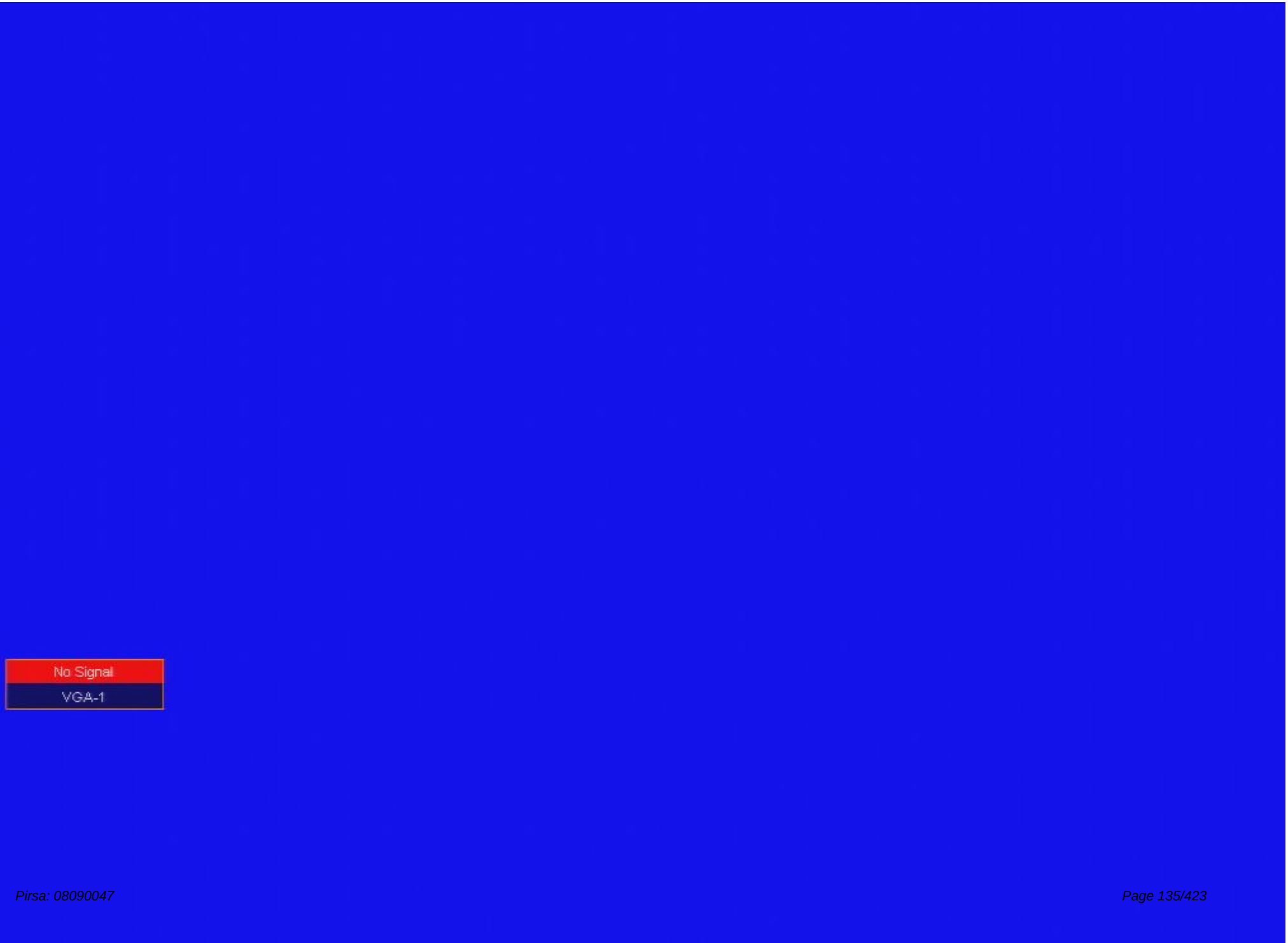

No Signal
VGA-1


No Signal
VGA-1

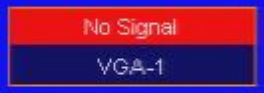

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

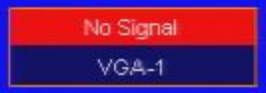

No Signal
VGA-1

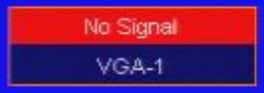

No Signal
VGA-1

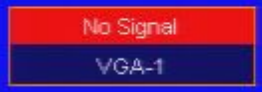

No Signal
VGA-1

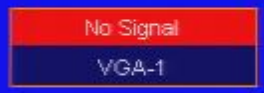

No Signal
VGA-1

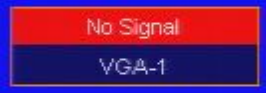

No Signal
VGA-1

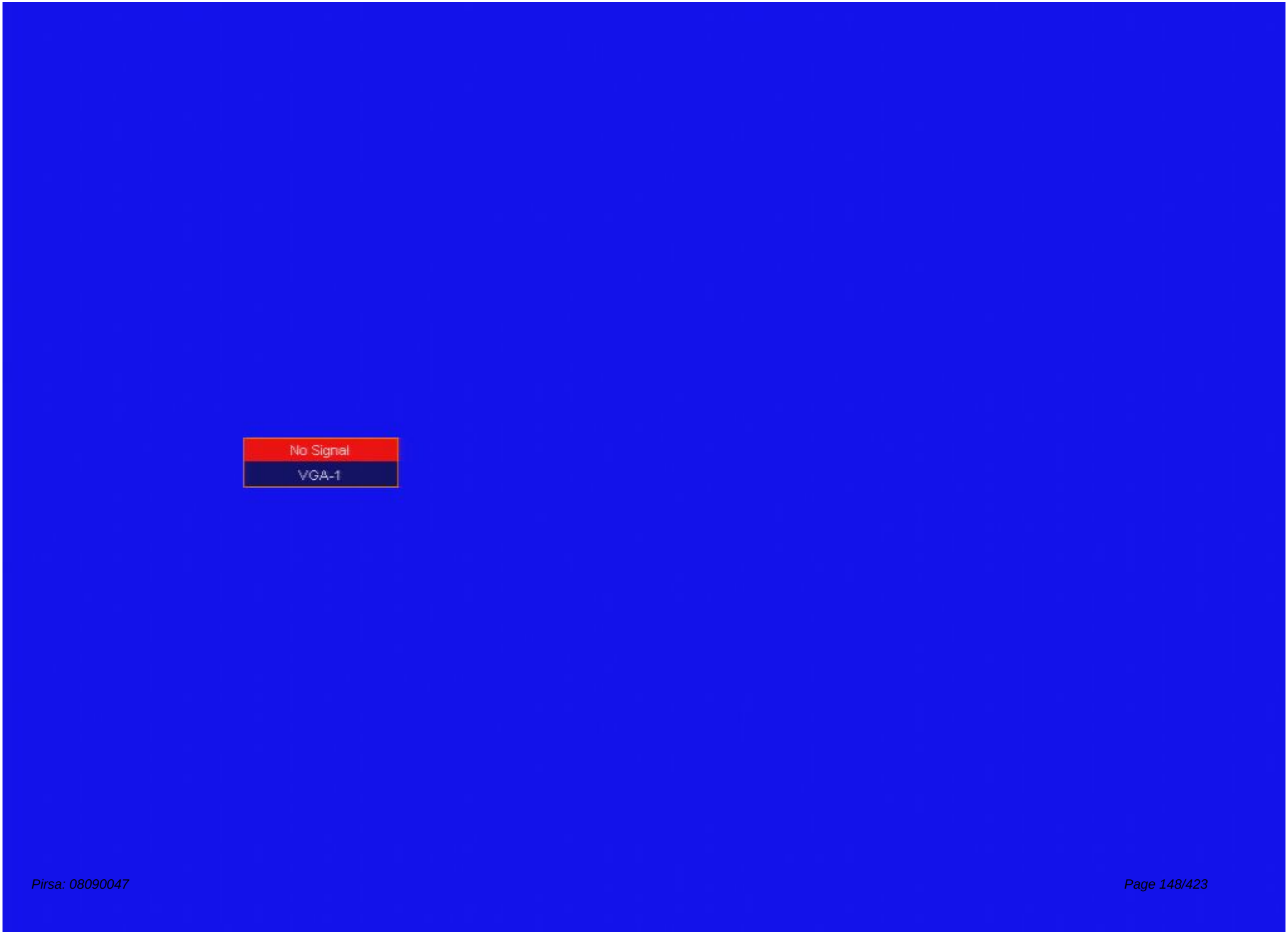

No Signal
VGA-1

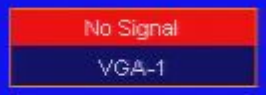

No Signal
VGA-1

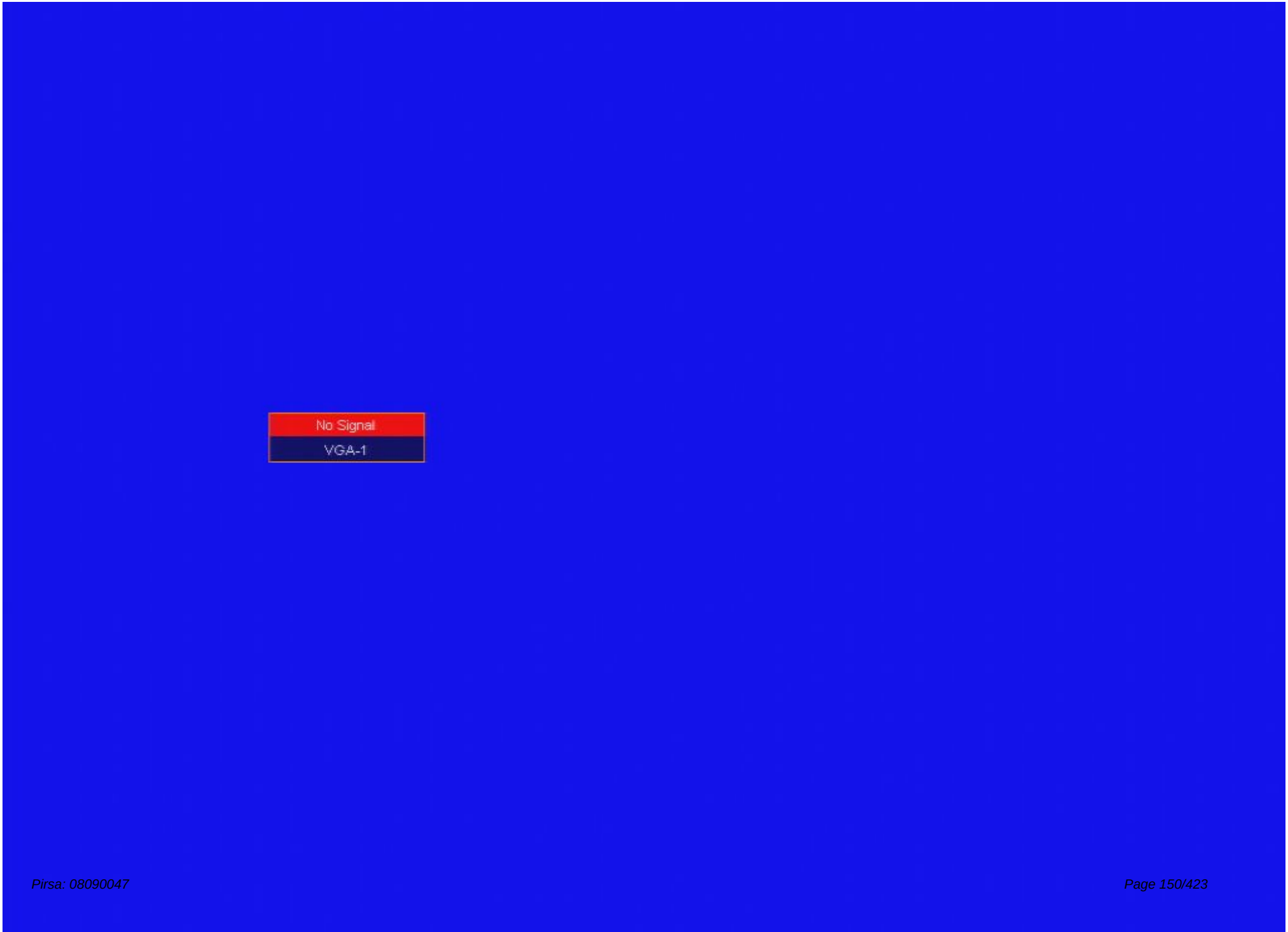

No Signal
VGA-1

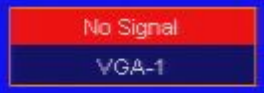

No Signal
VGA-1

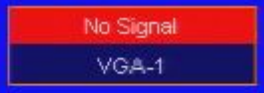

No Signal
VGA-1


No Signal
VGA-1

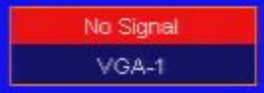

No Signal
VGA-1

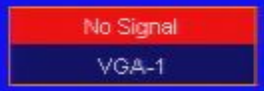

No Signal
VGA-1


No Signal
VGA-1

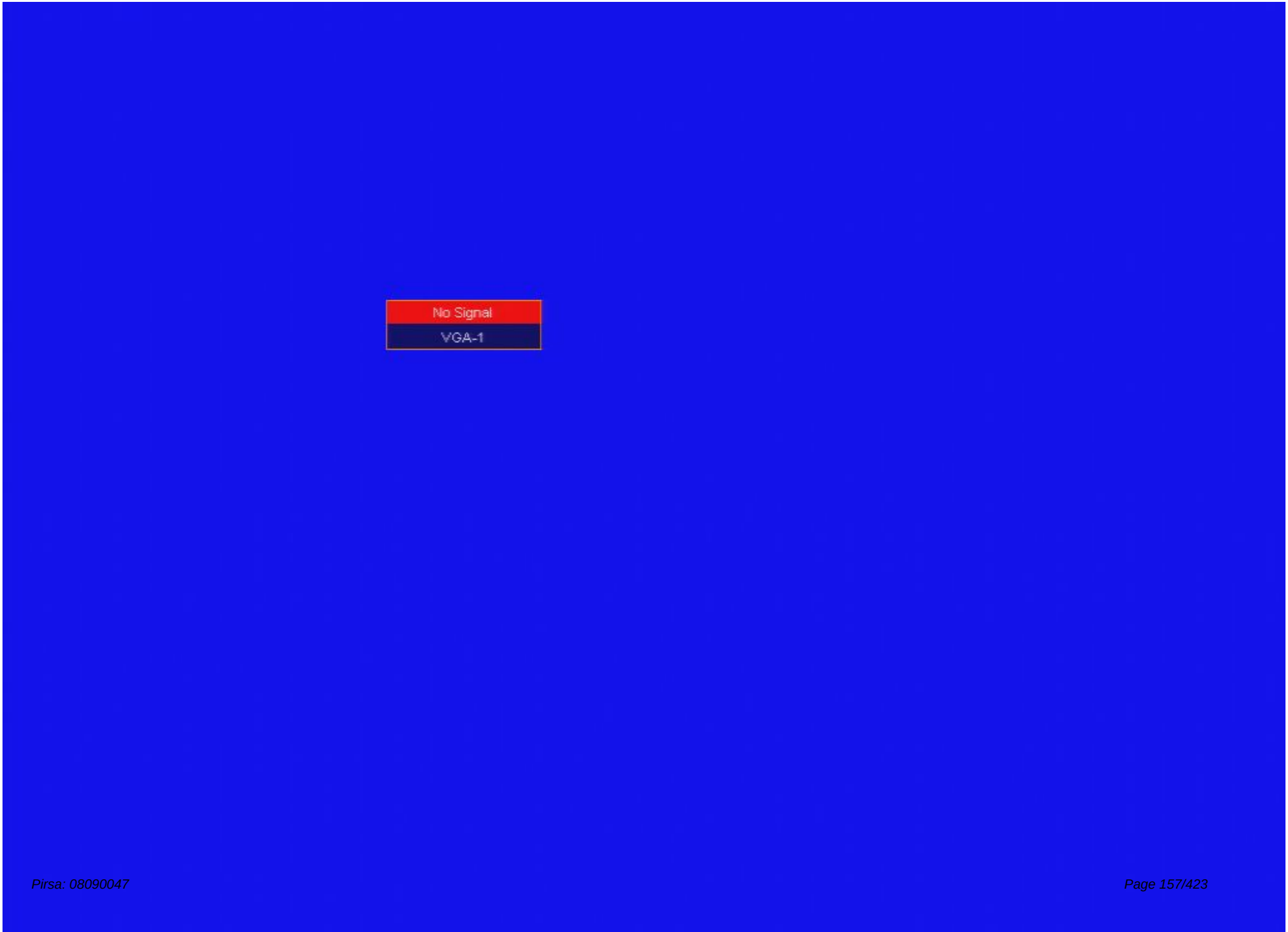

No Signal
VGA-1

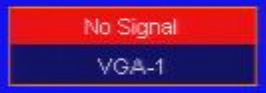

No Signal
VGA-1

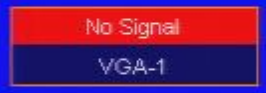

No Signal
VGA-1

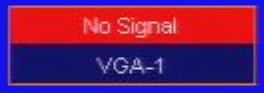

No Signal
VGA-1

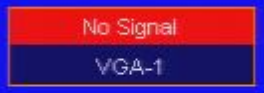

No Signal
VGA-1

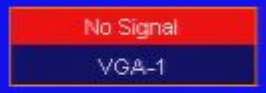

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

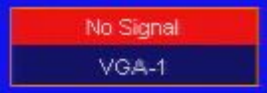

No Signal
VGA-1


No Signal
VGA-1

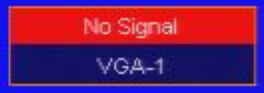

No Signal
VGA-1


No Signal
VGA-1

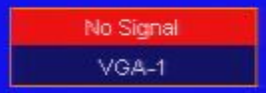

No Signal
VGA-1

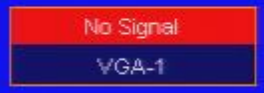

No Signal
VGA-1

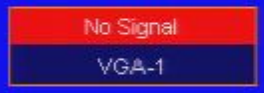

No Signal
VGA-1

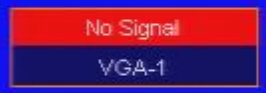

No Signal
VGA-1

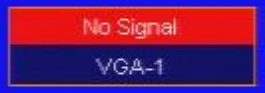

No Signal
VGA-1

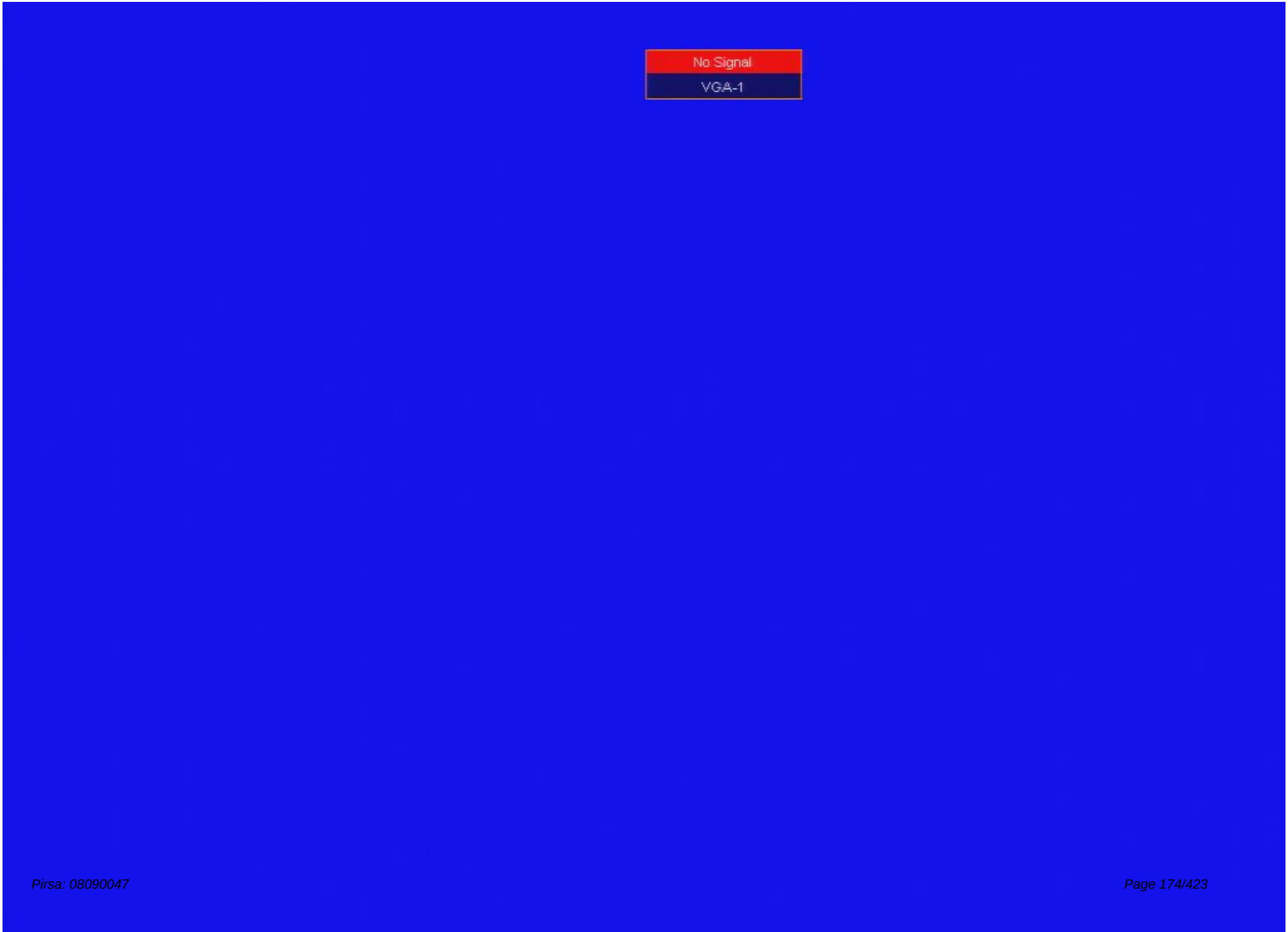

No Signal
VGA-1

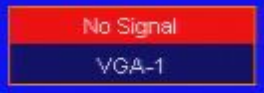

No Signal
VGA-1

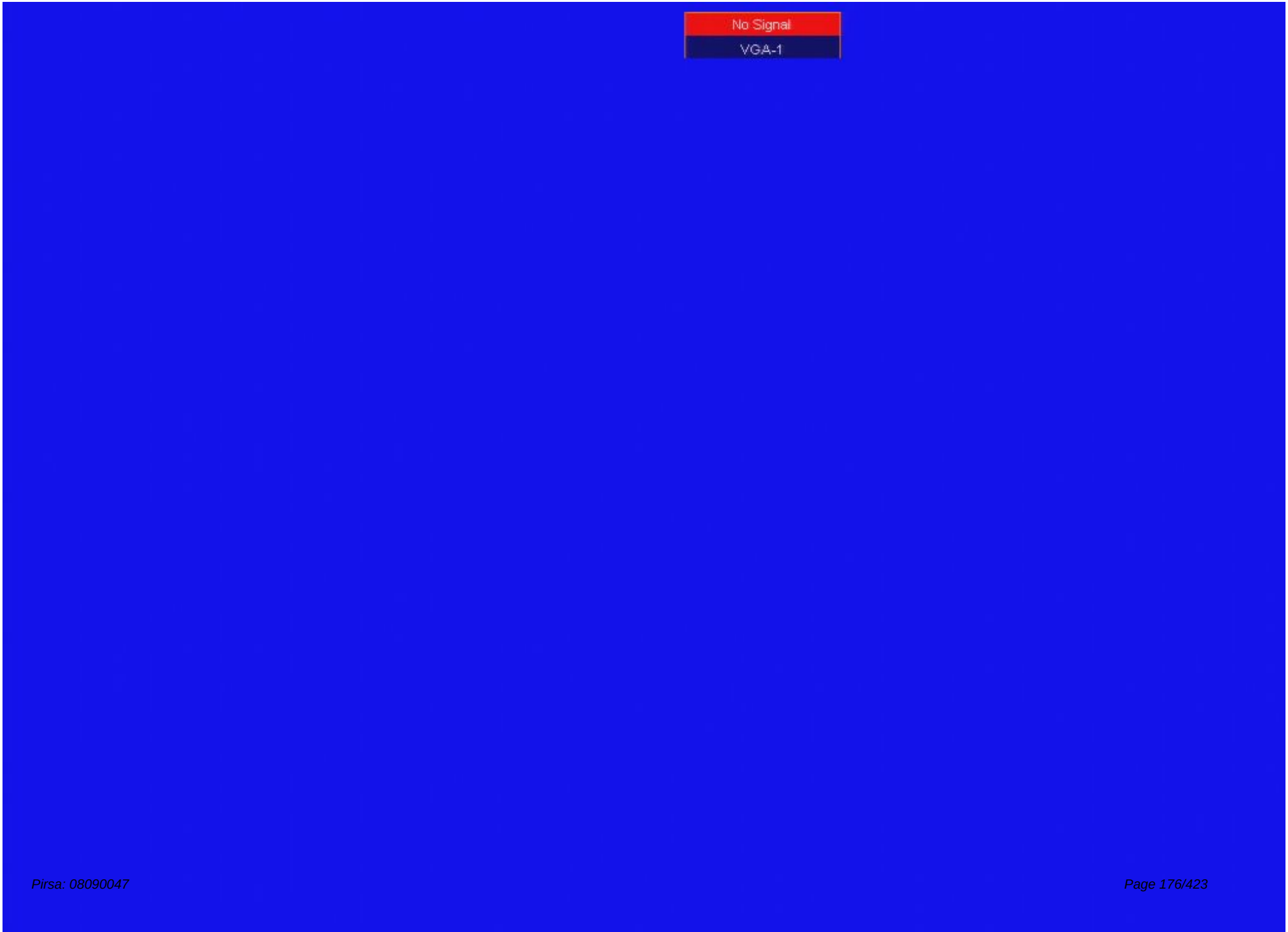

No Signal
VGA-1

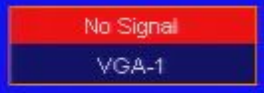

No Signal
VGA-1

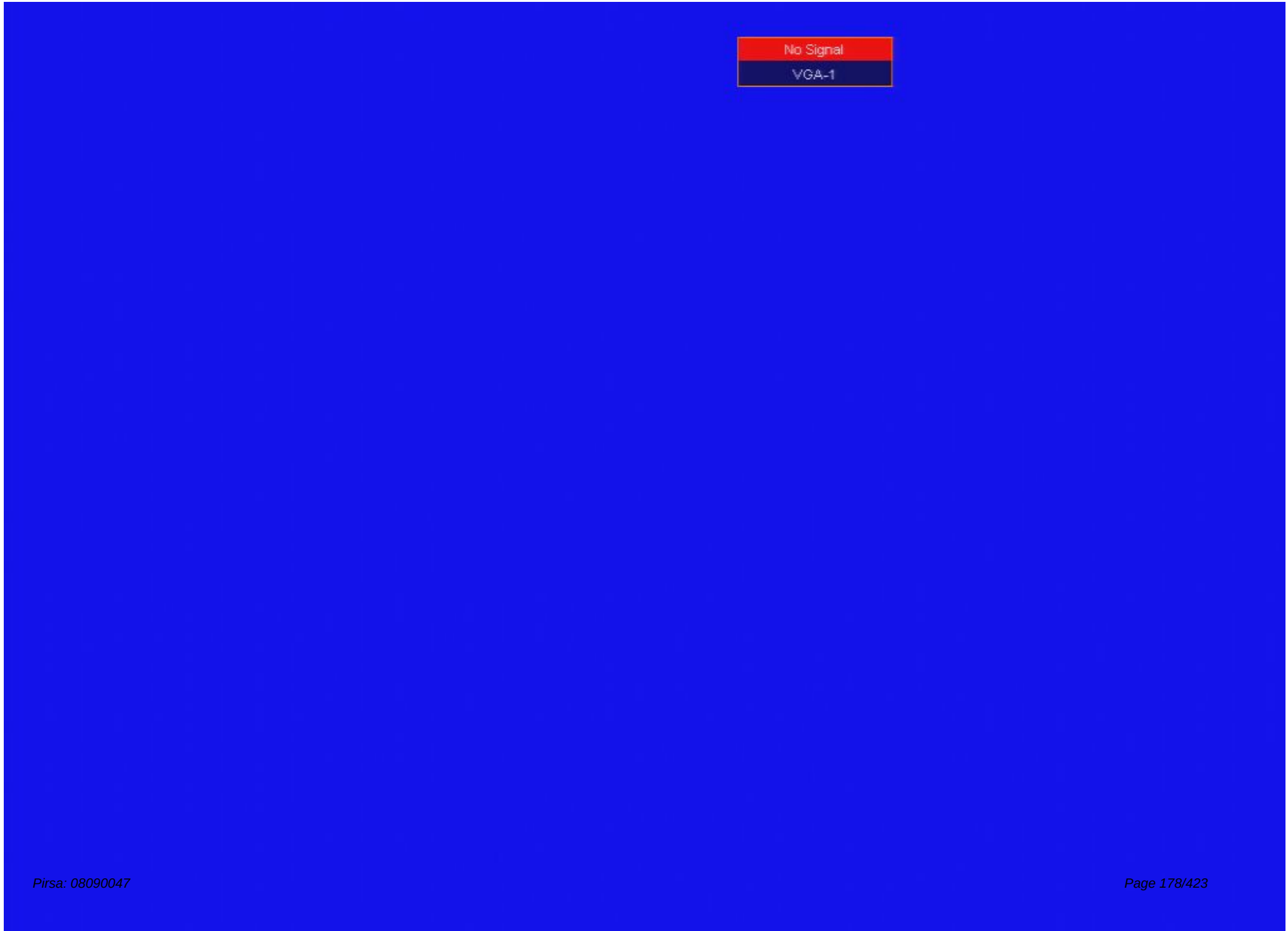

No Signal
VGA-1

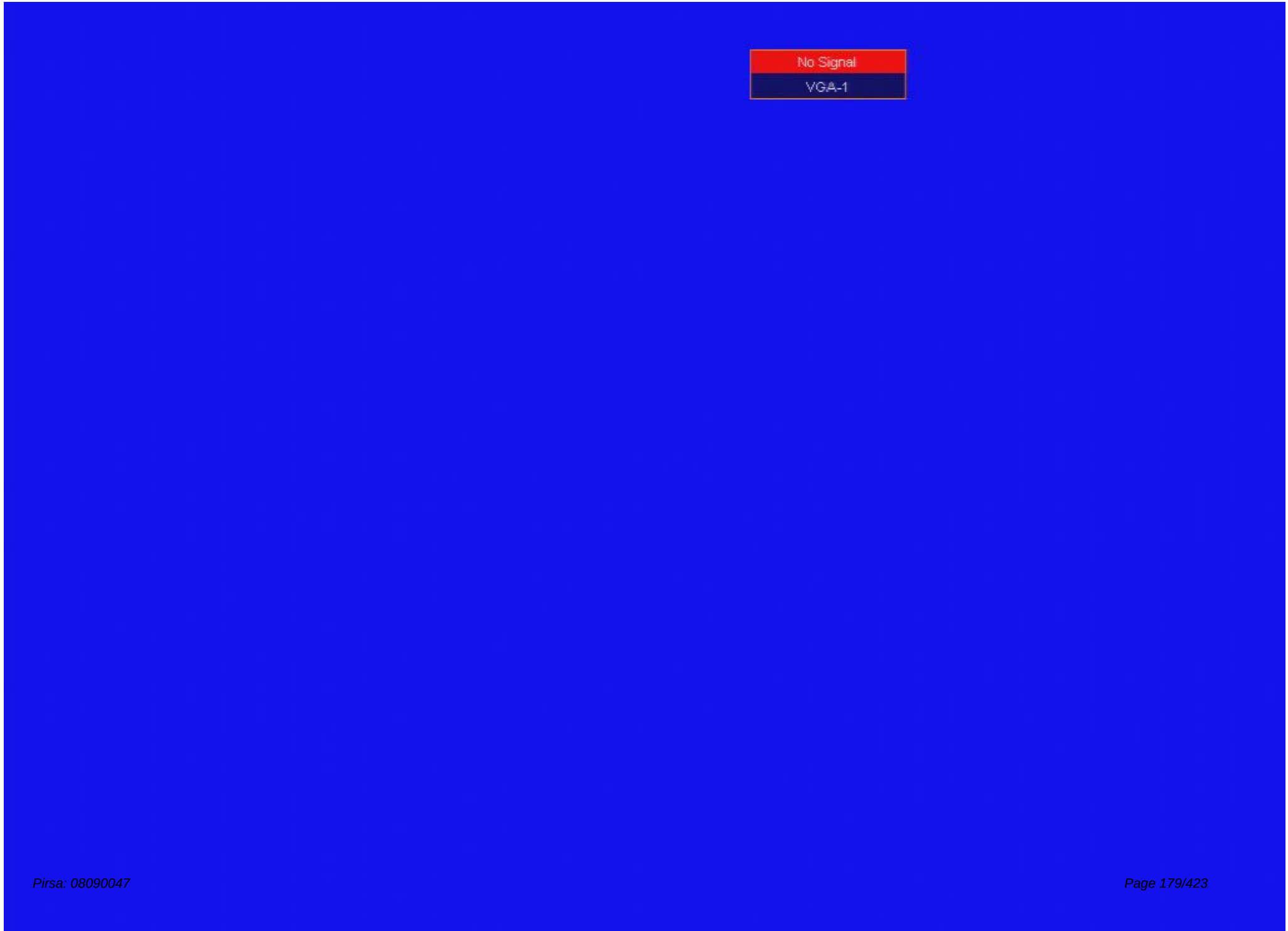

No Signal
VGA-1

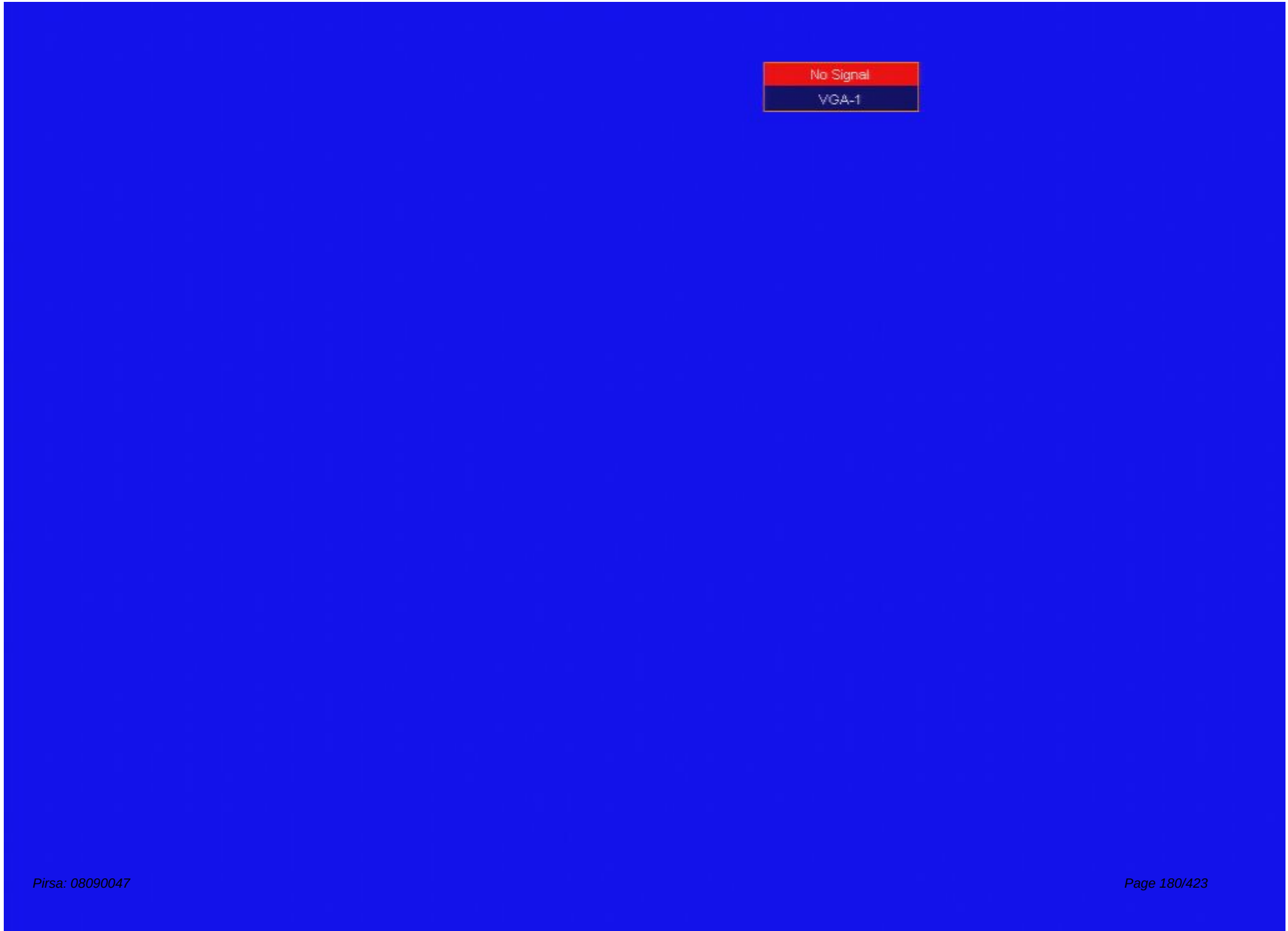

No Signal
VGA-1

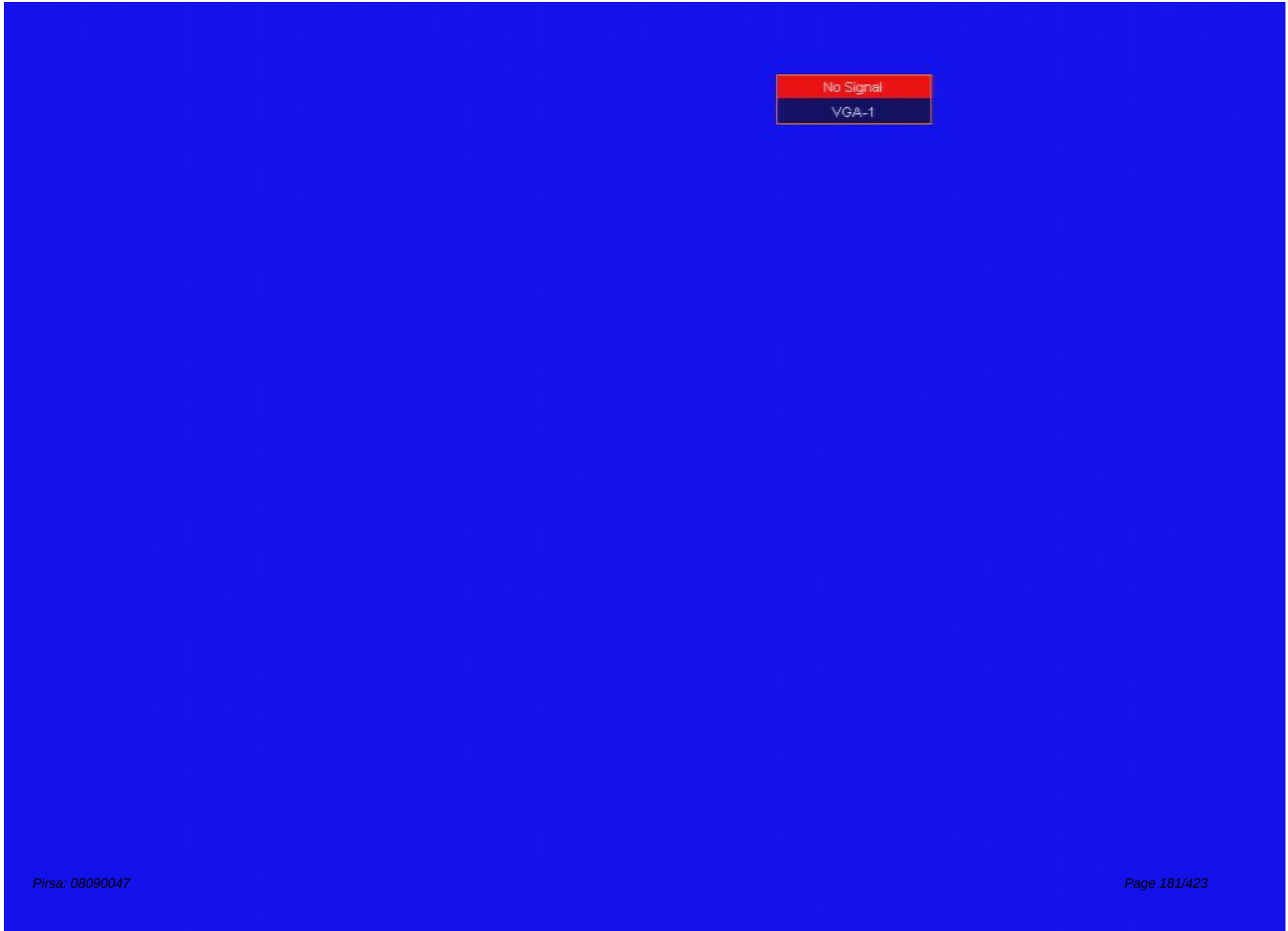

No Signal
VGA-1

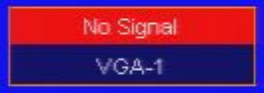

No Signal
VGA-1

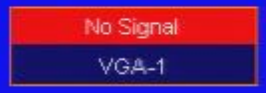

No Signal
VGA-1

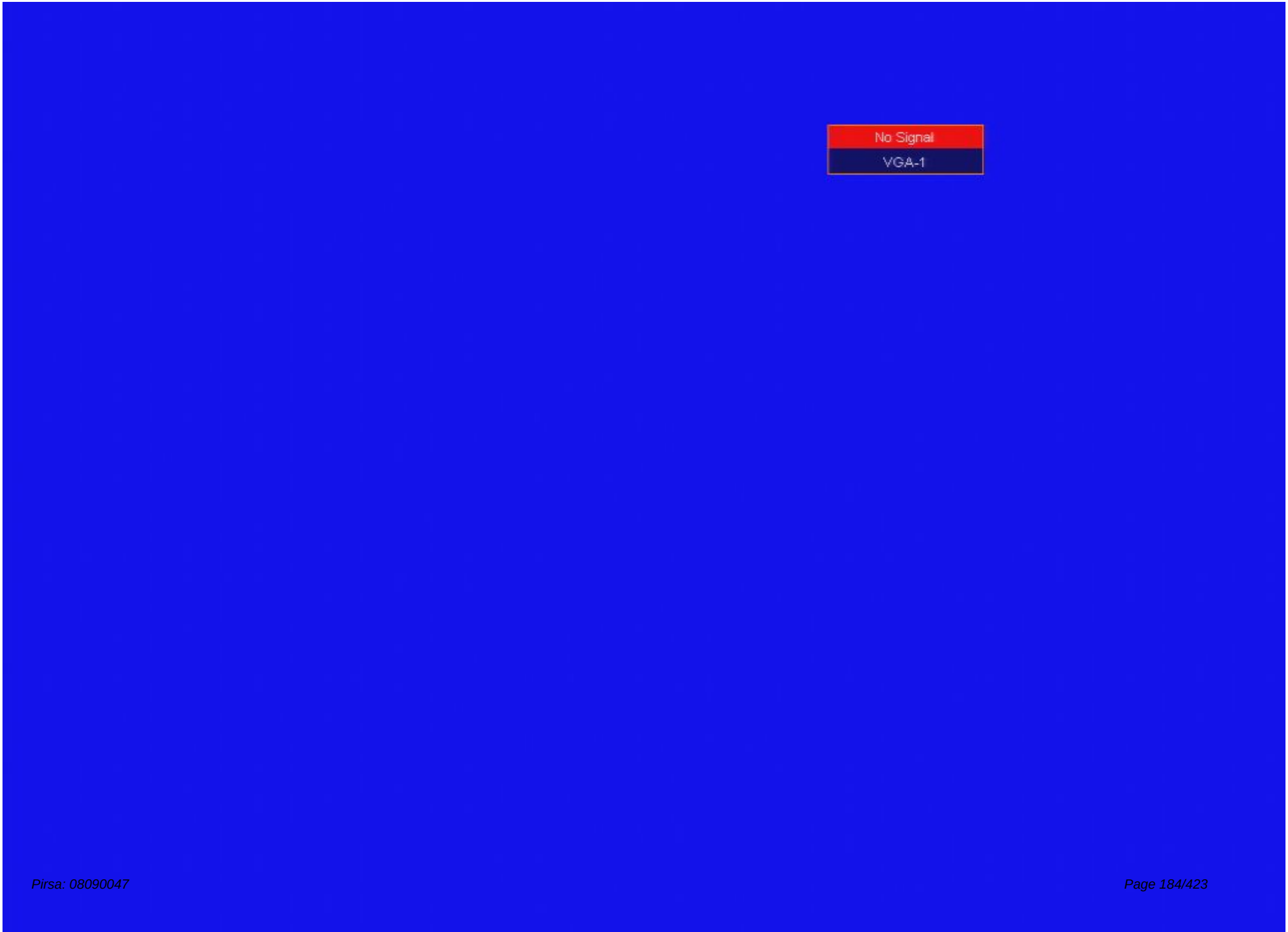

No Signal
VGA-1

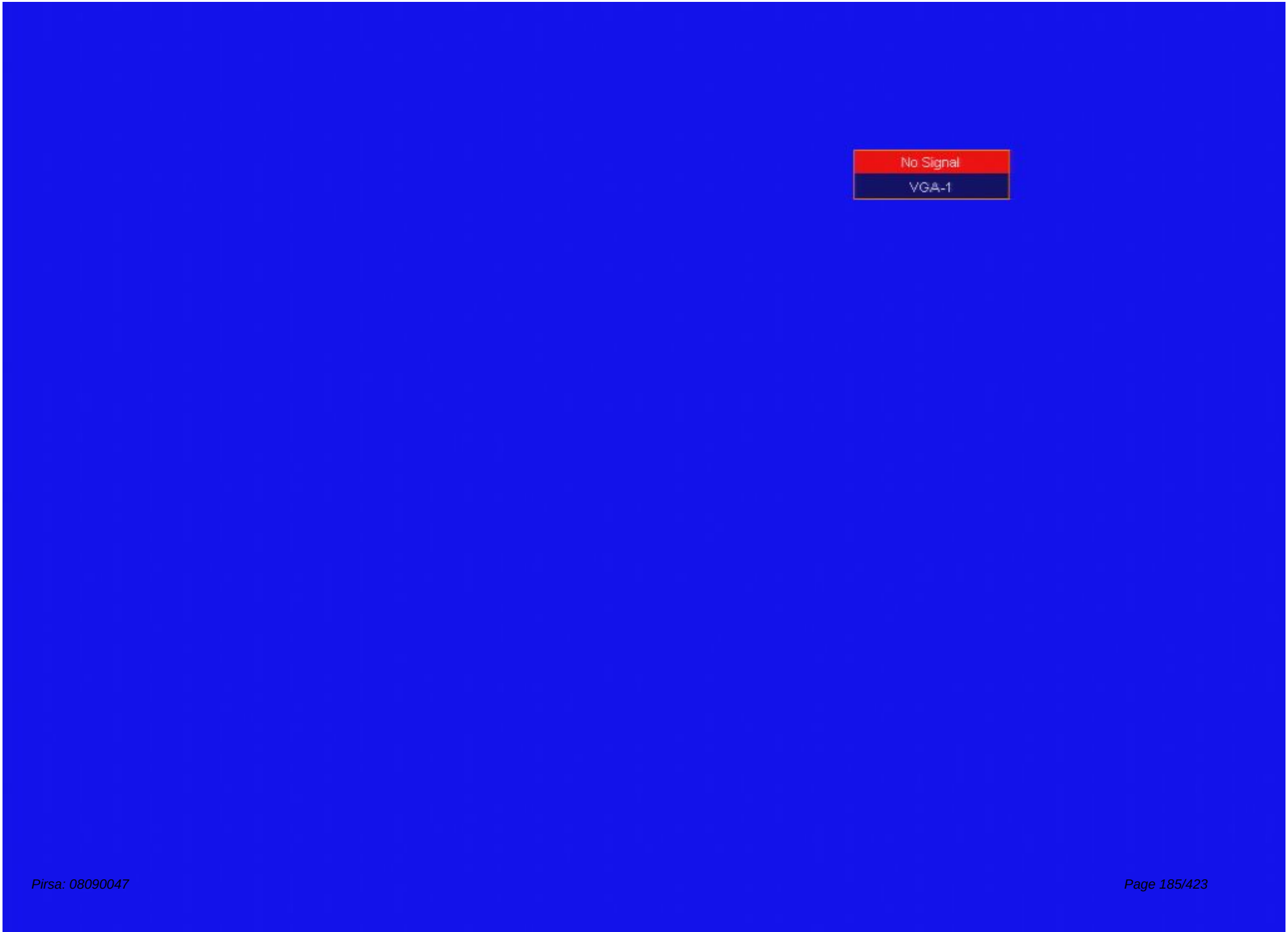

No Signal
VGA-1

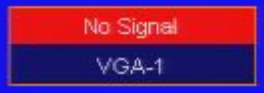

No Signal
VGA-1

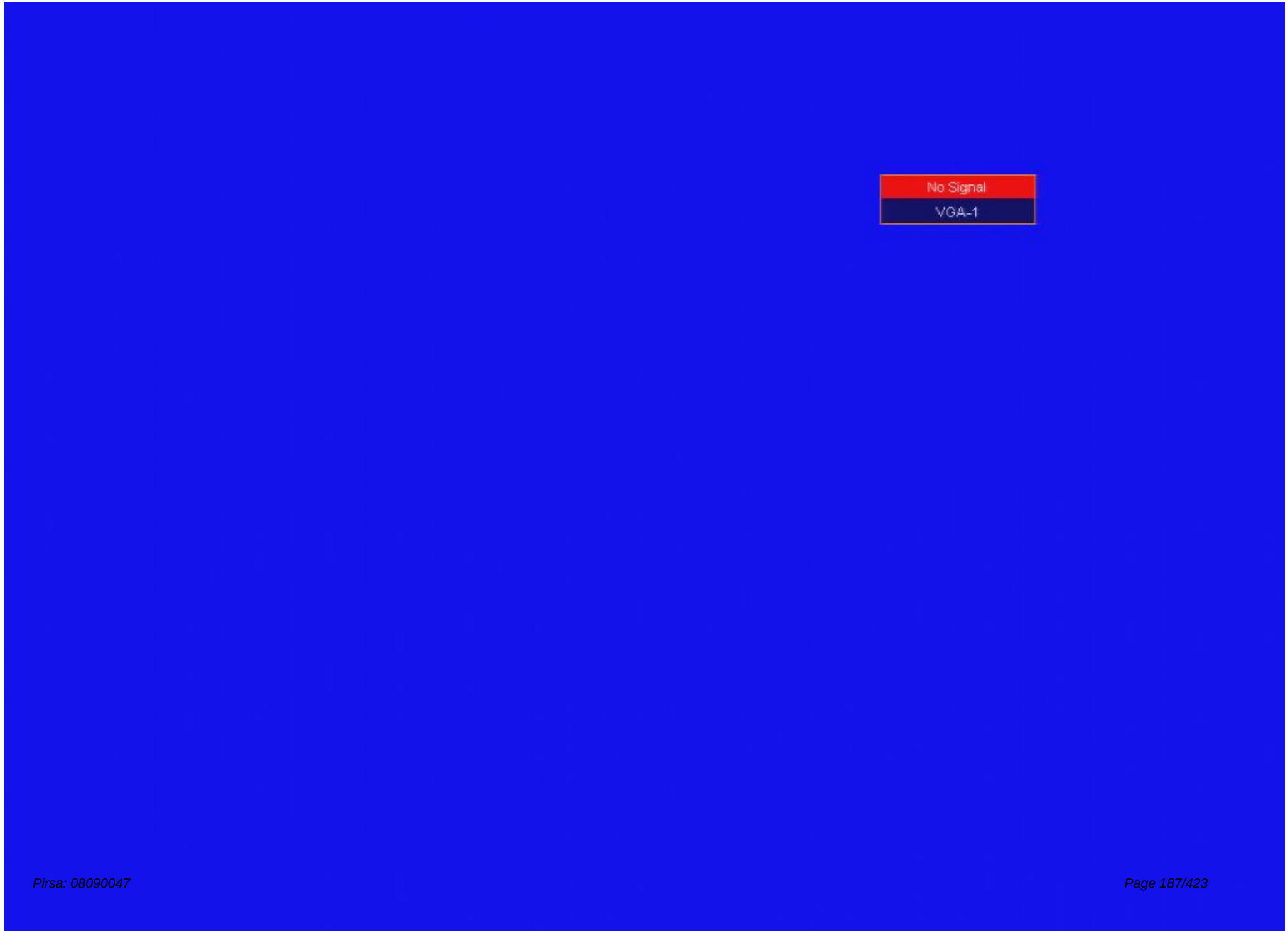

No Signal
VGA-1

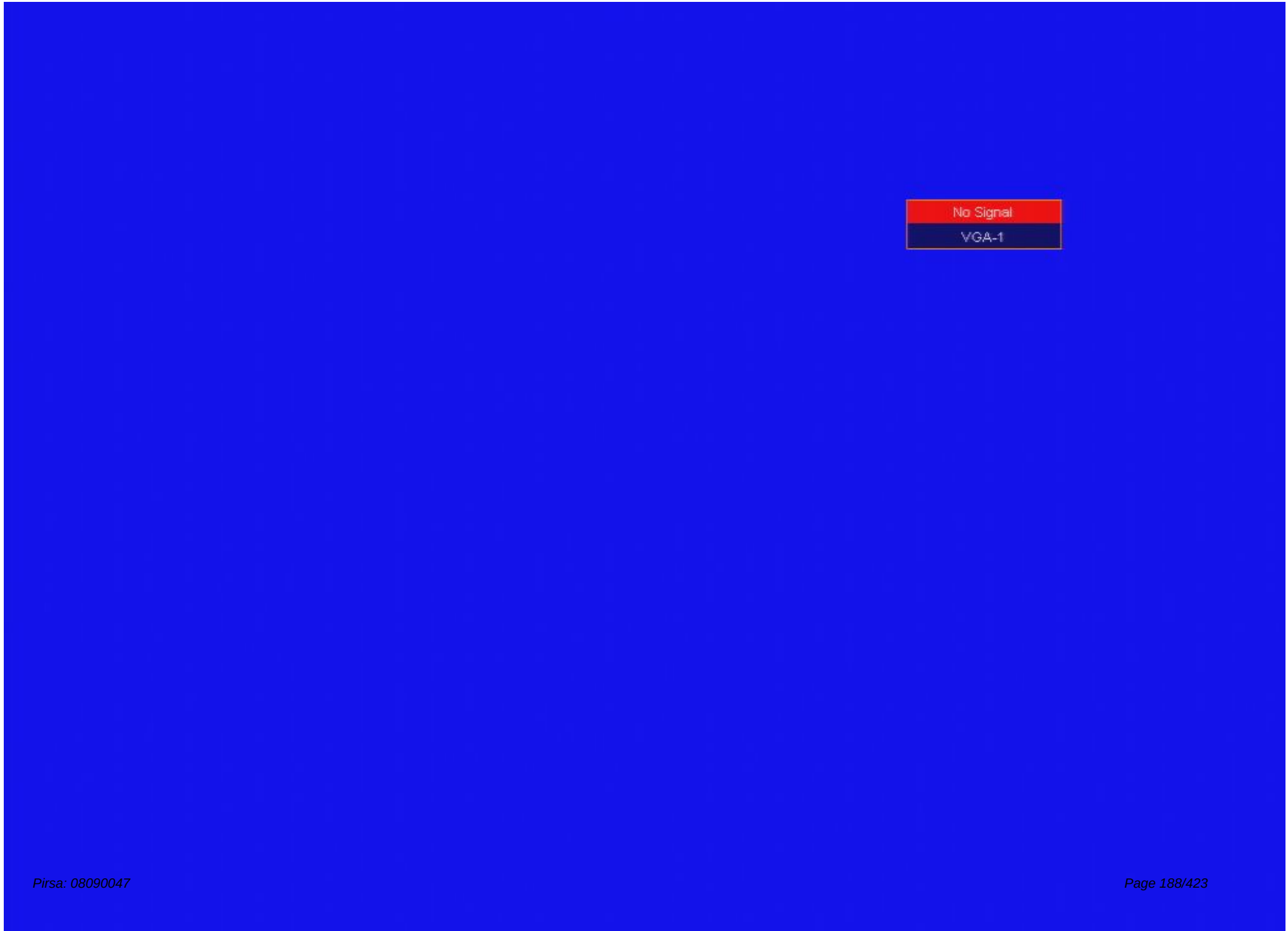

No Signal
VGA-1

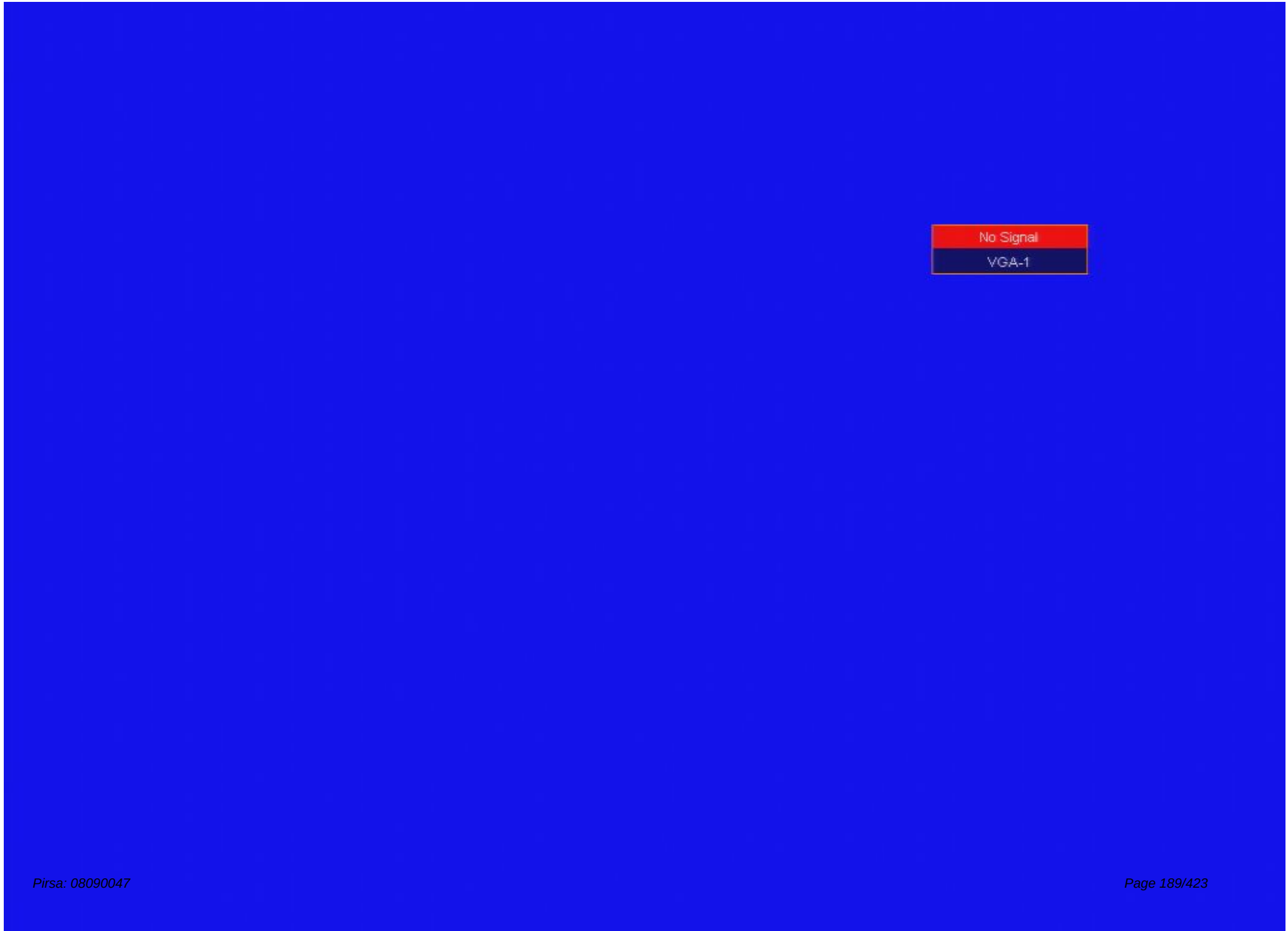

No Signal
VGA-1

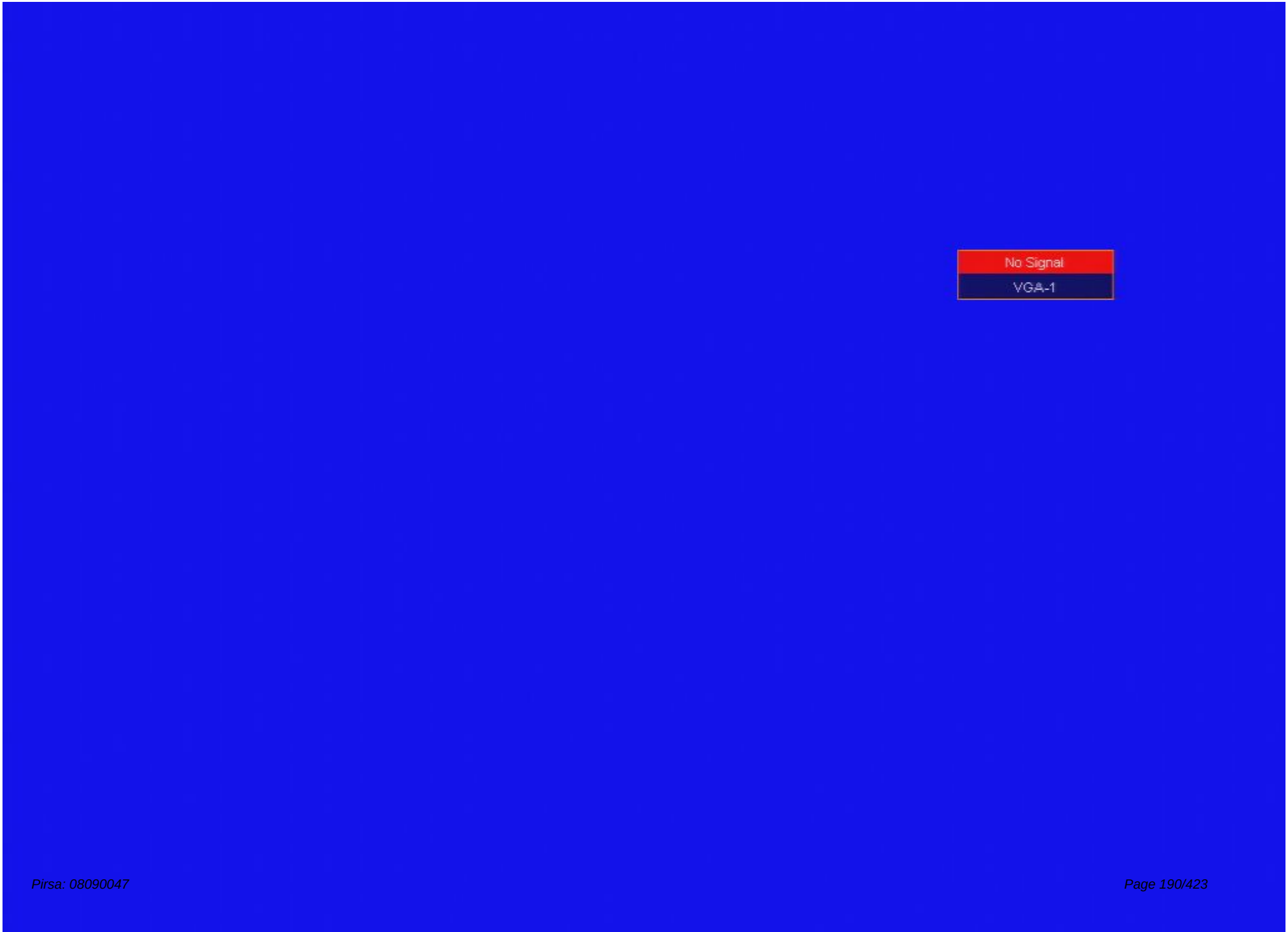

No Signal
VGA-1

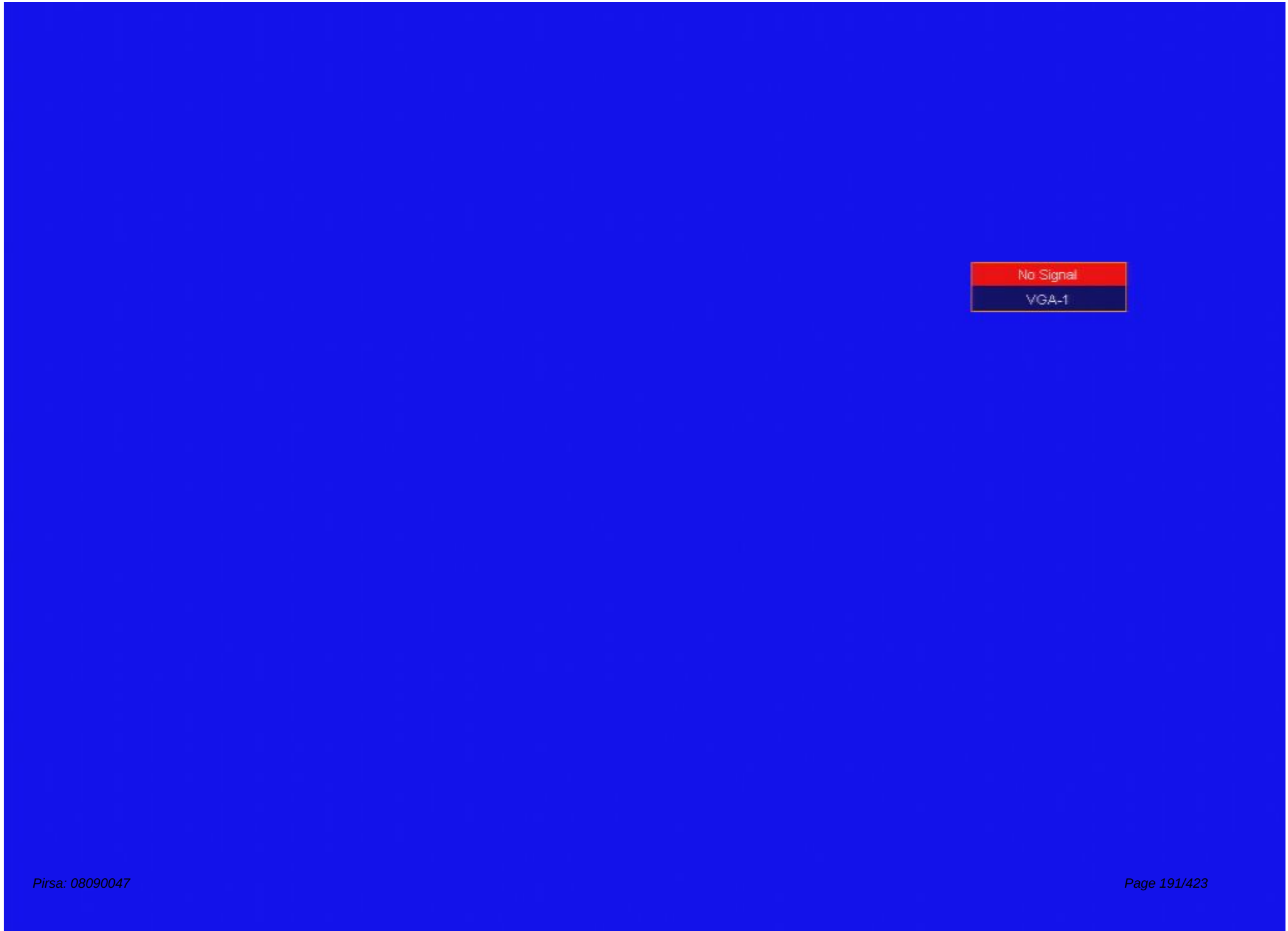

No Signal
VGA-1

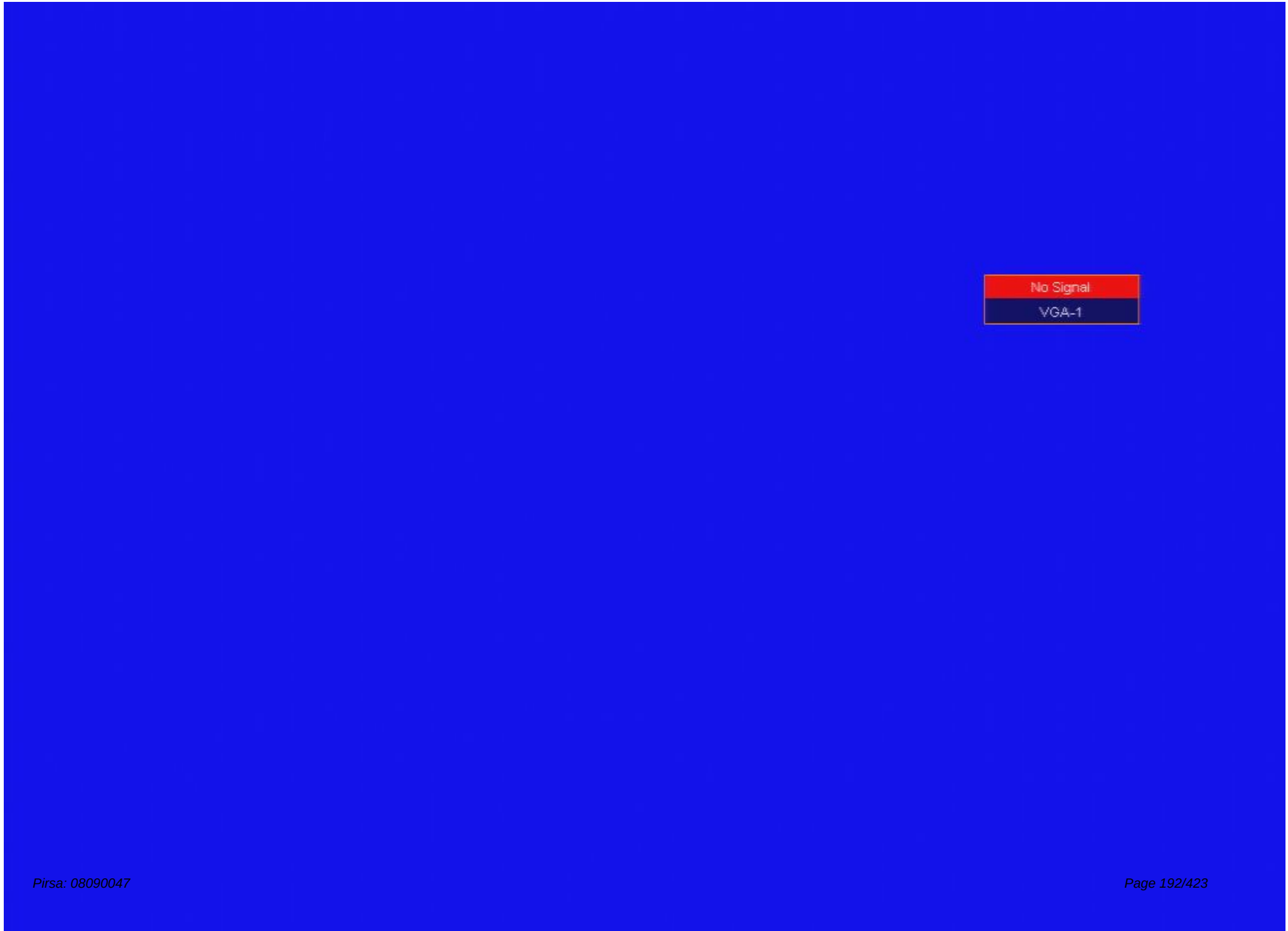

No Signal
VGA-1

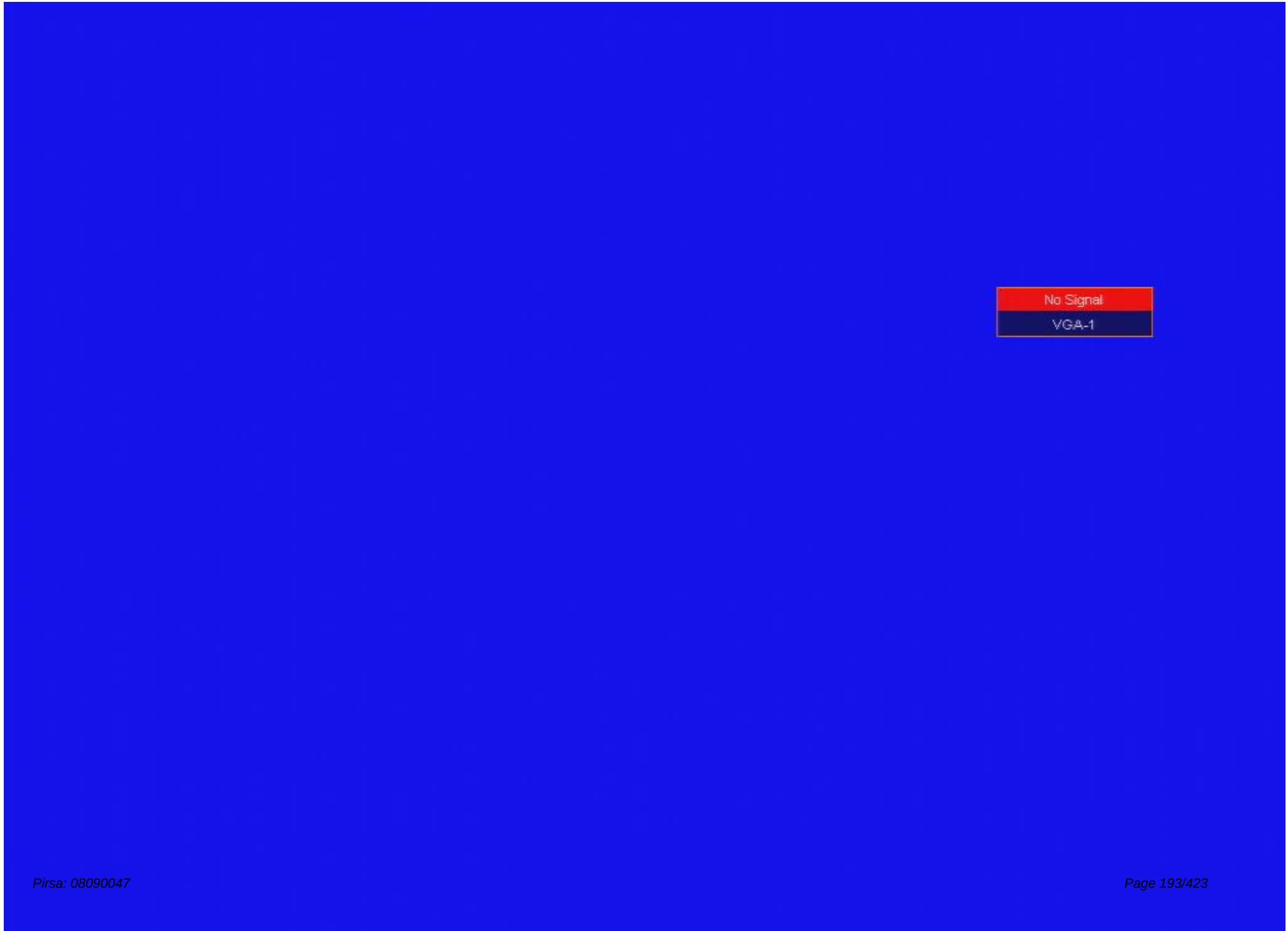

No Signal
VGA-1

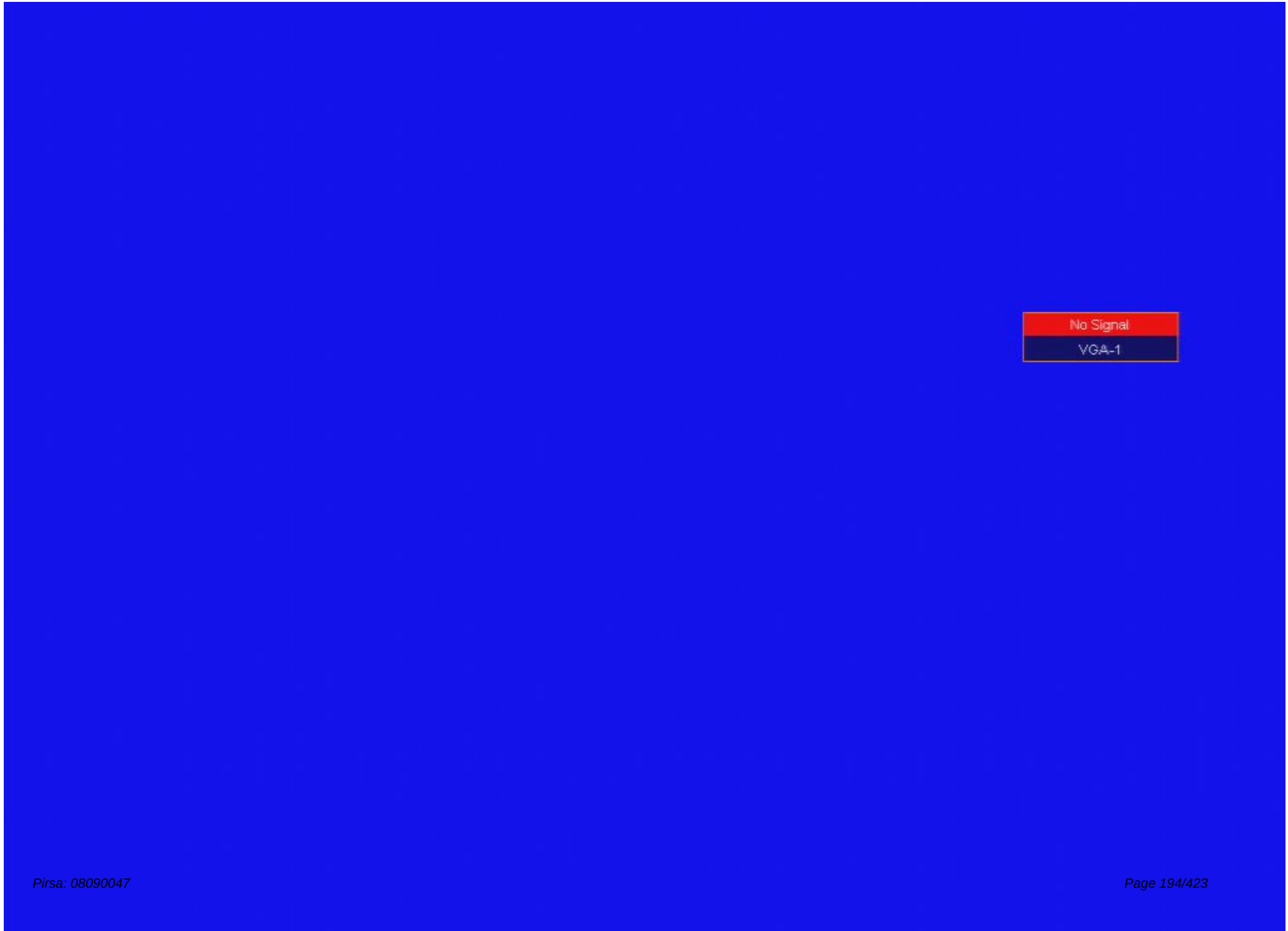

No Signal
VGA-1

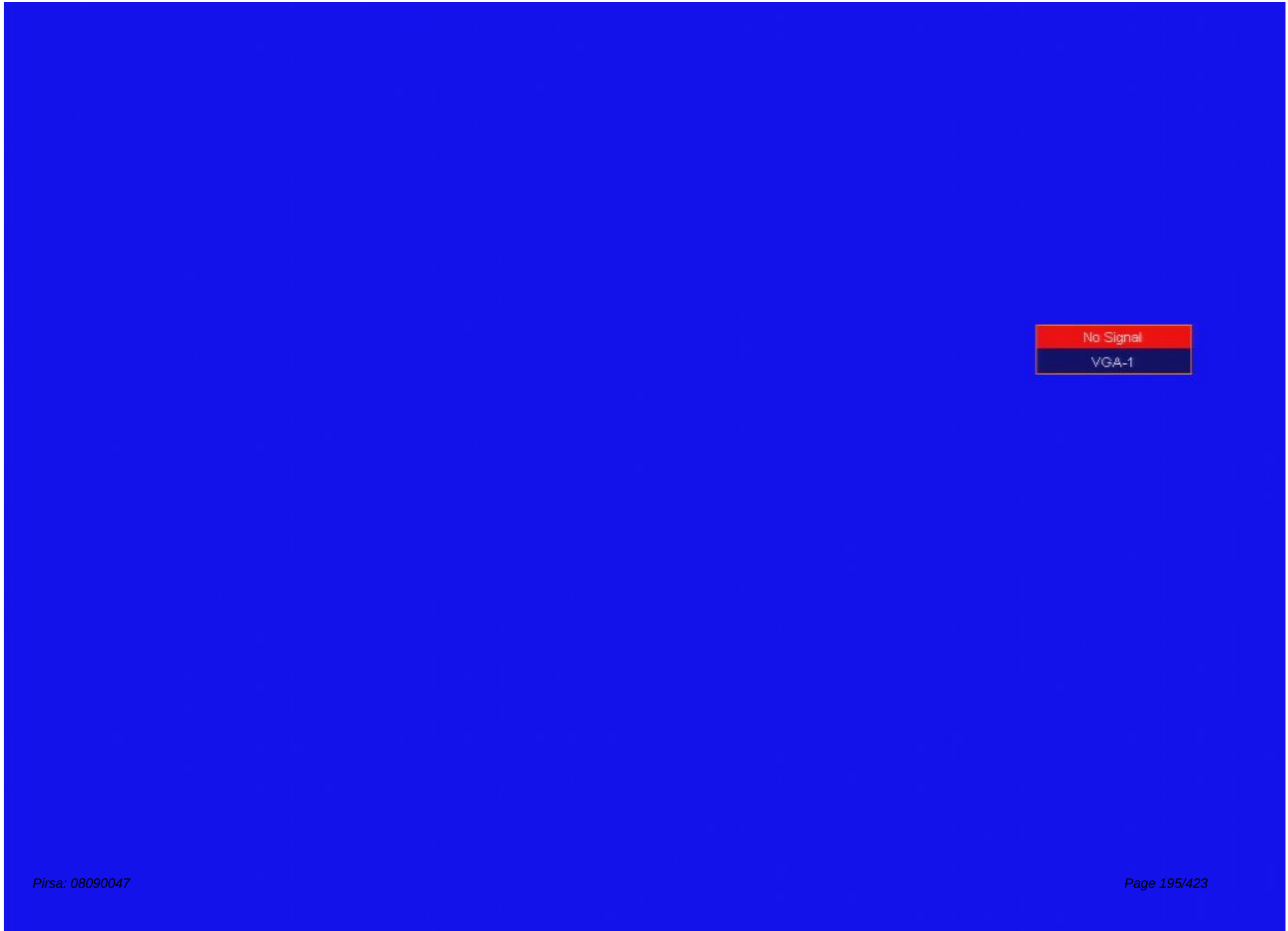

No Signal
VGA-1

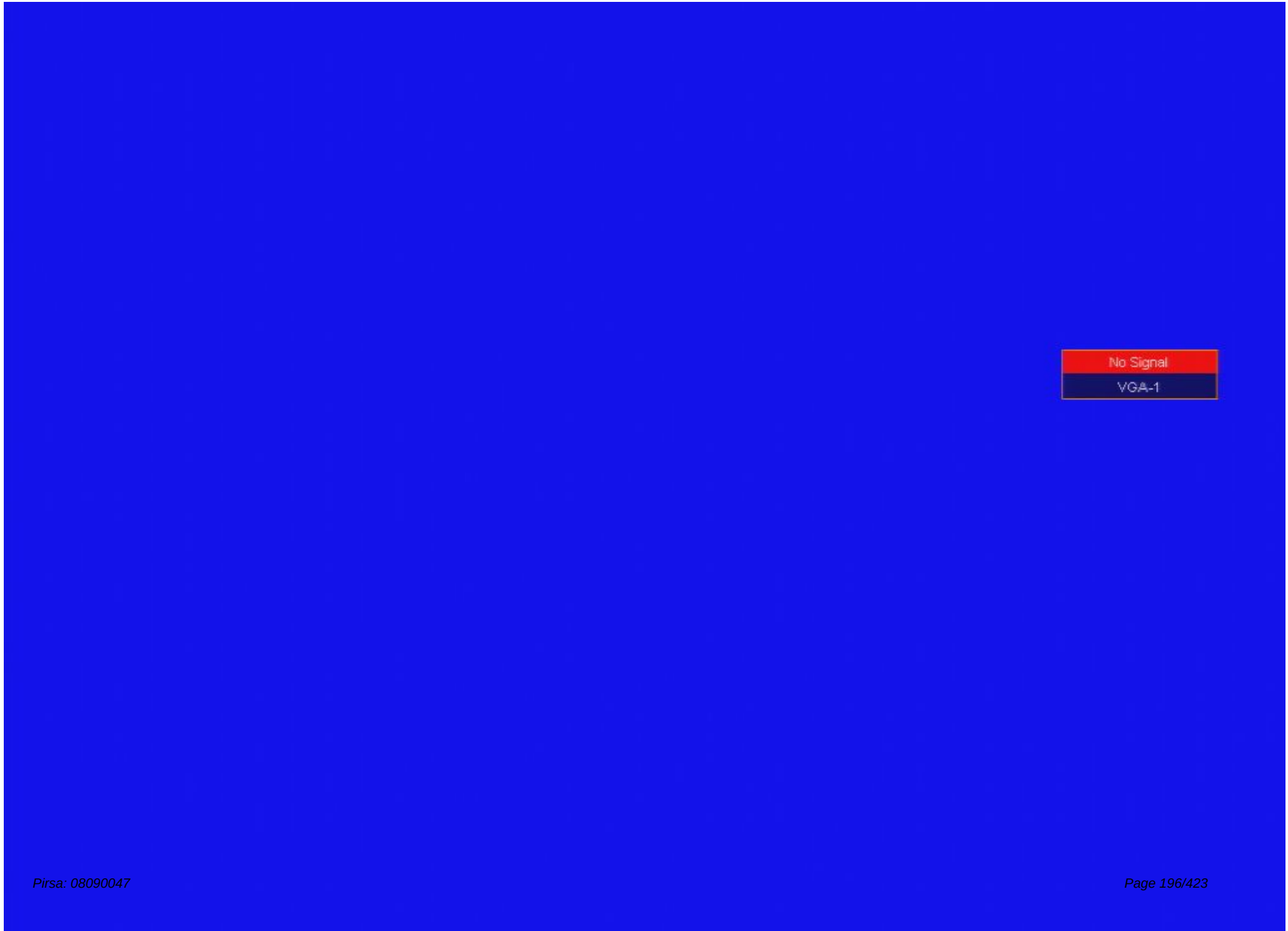

No Signal
VGA-1

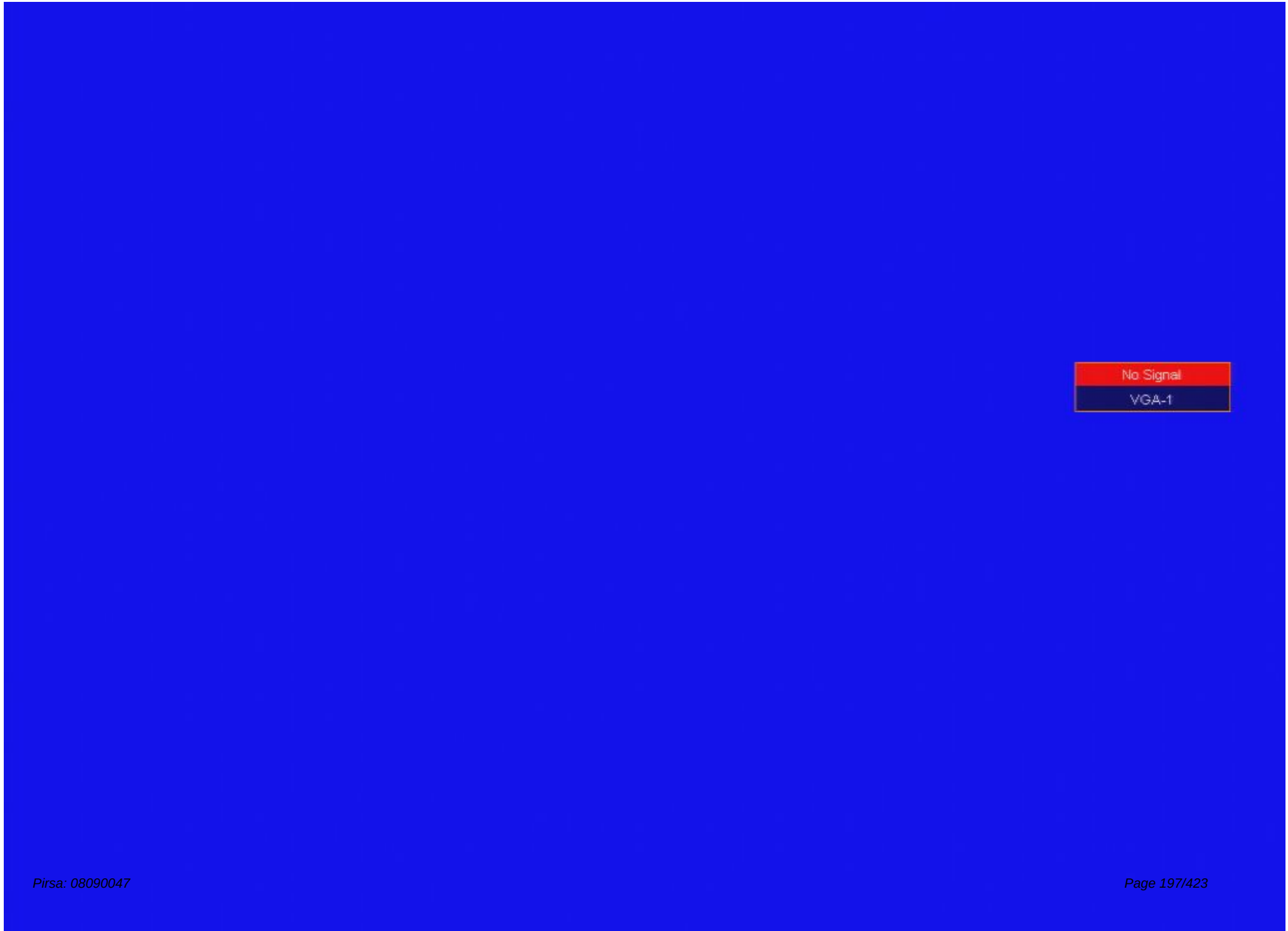

No Signal
VGA-1

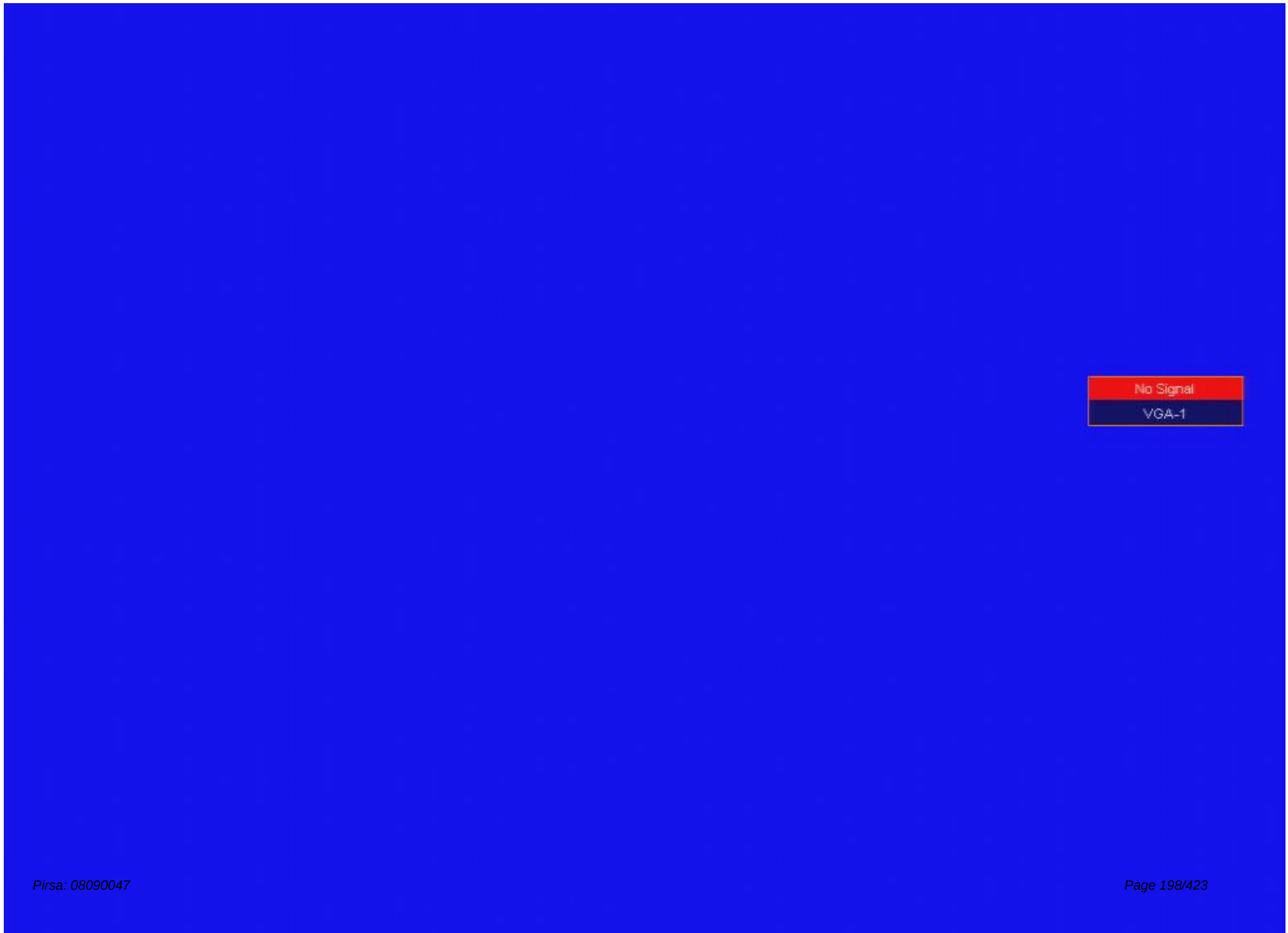

No Signal
VGA-1


No Signal
VGA-1

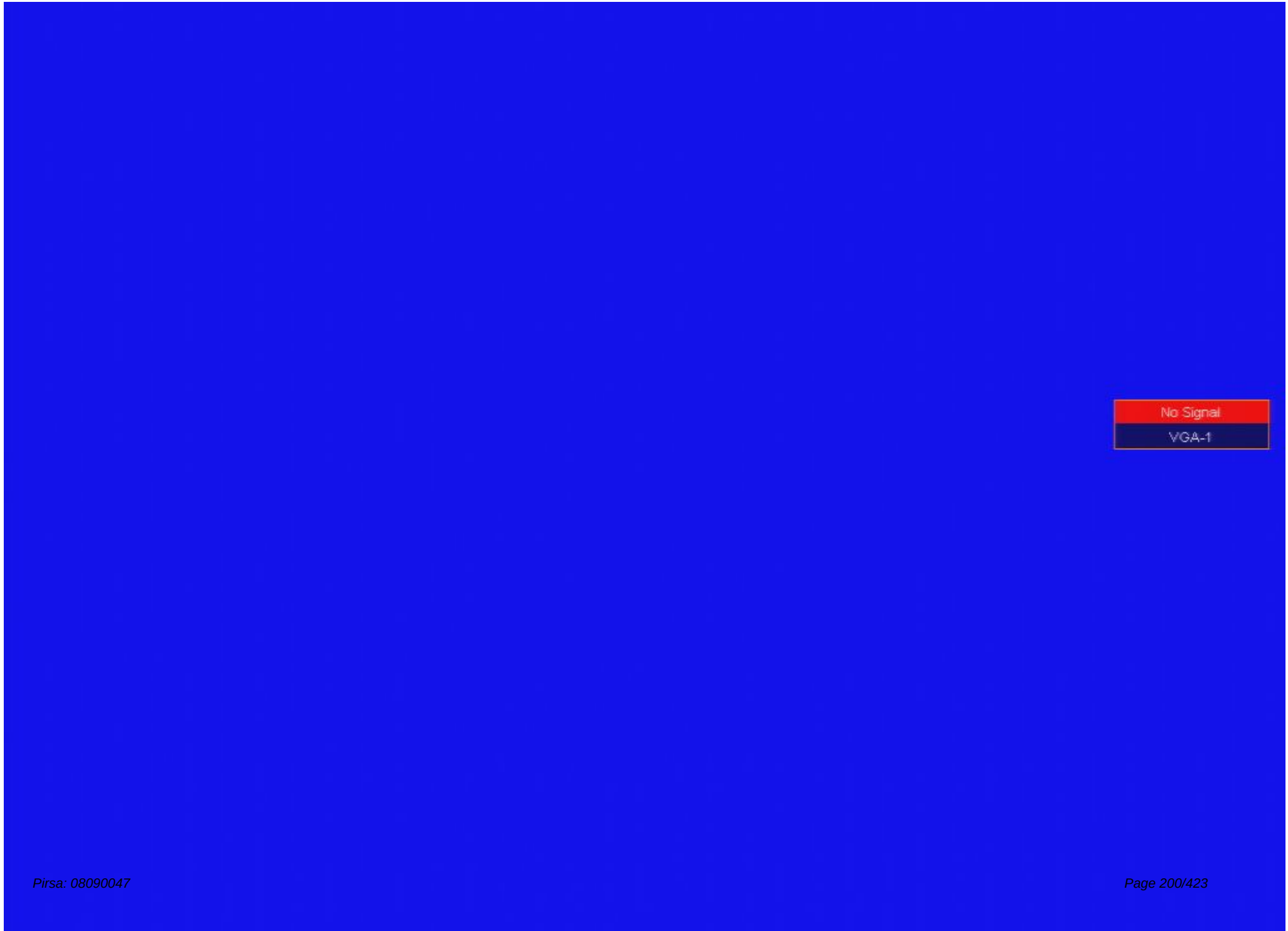

No Signal
VGA-1

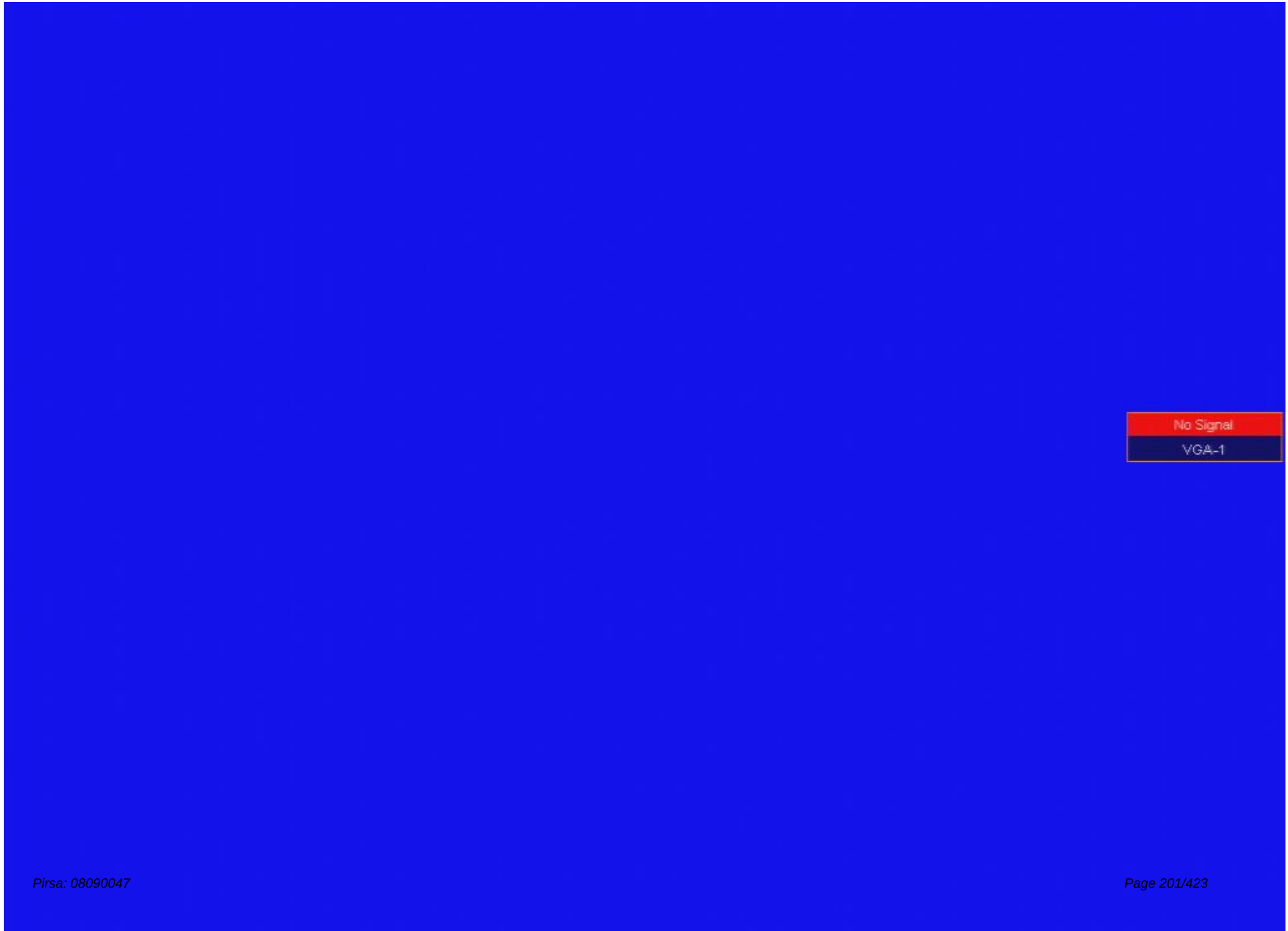

No Signal
VGA-1

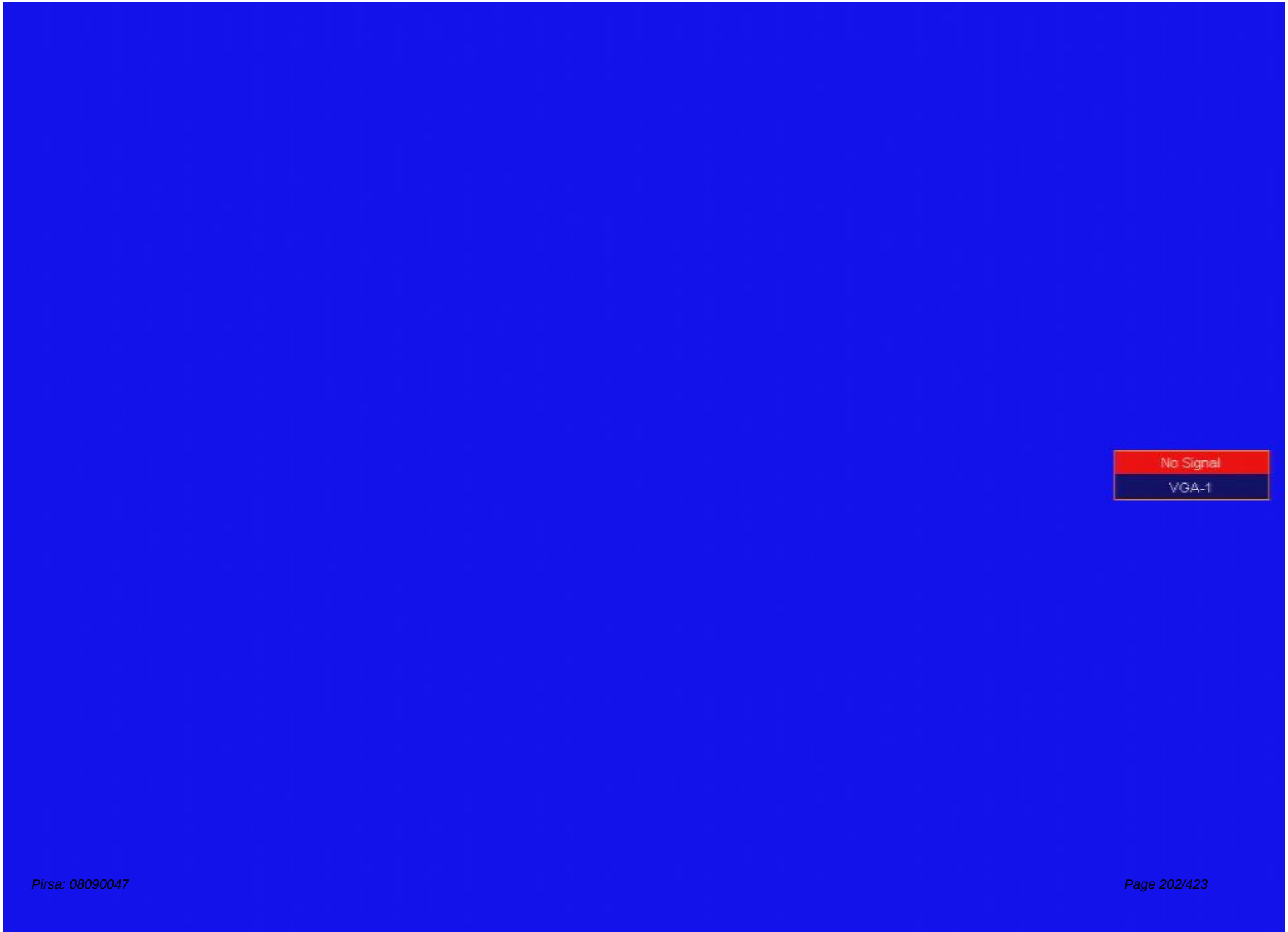

No Signal
VGA-1

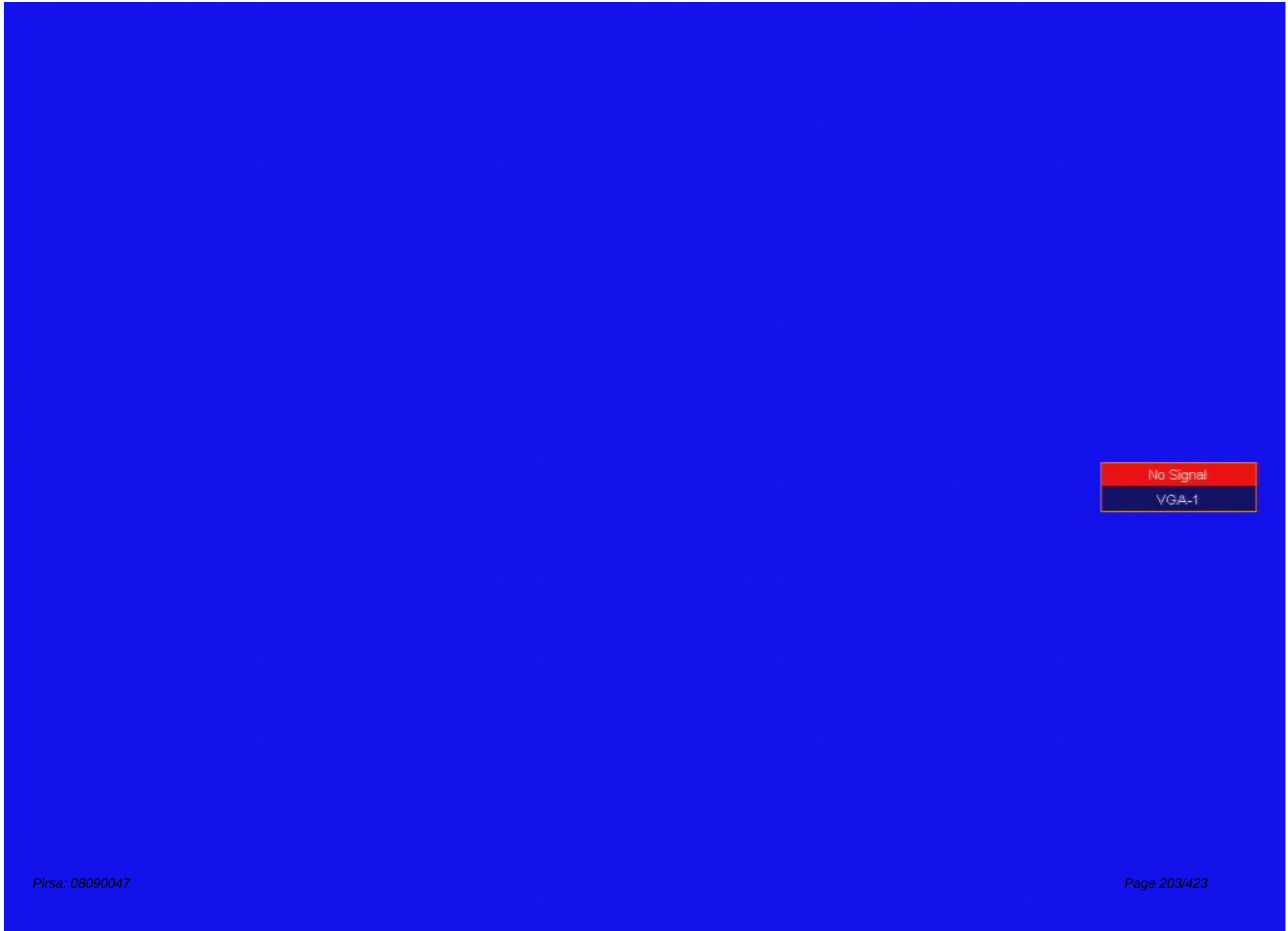

No Signal
VGA-1

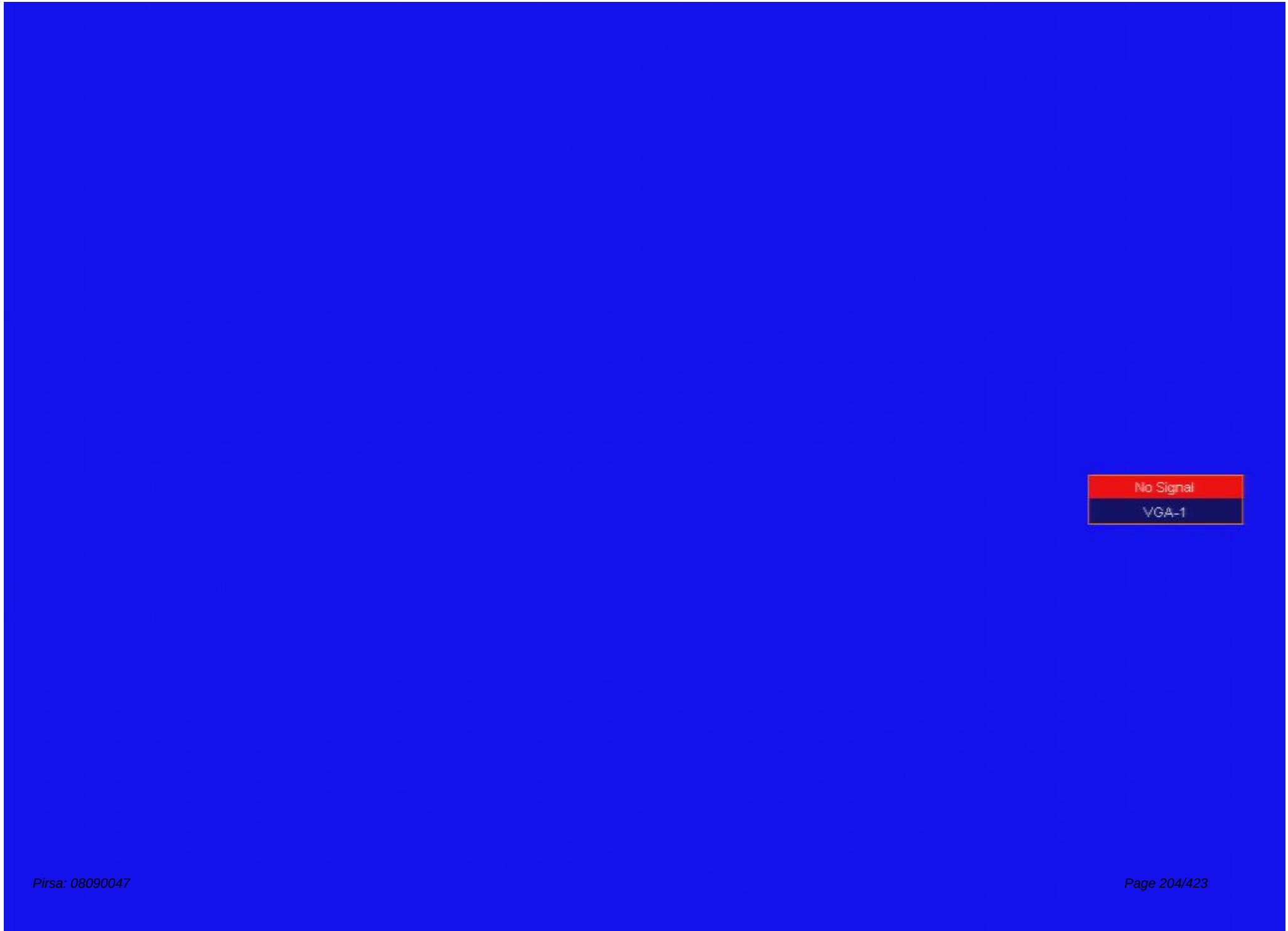

No Signal
VGA-1

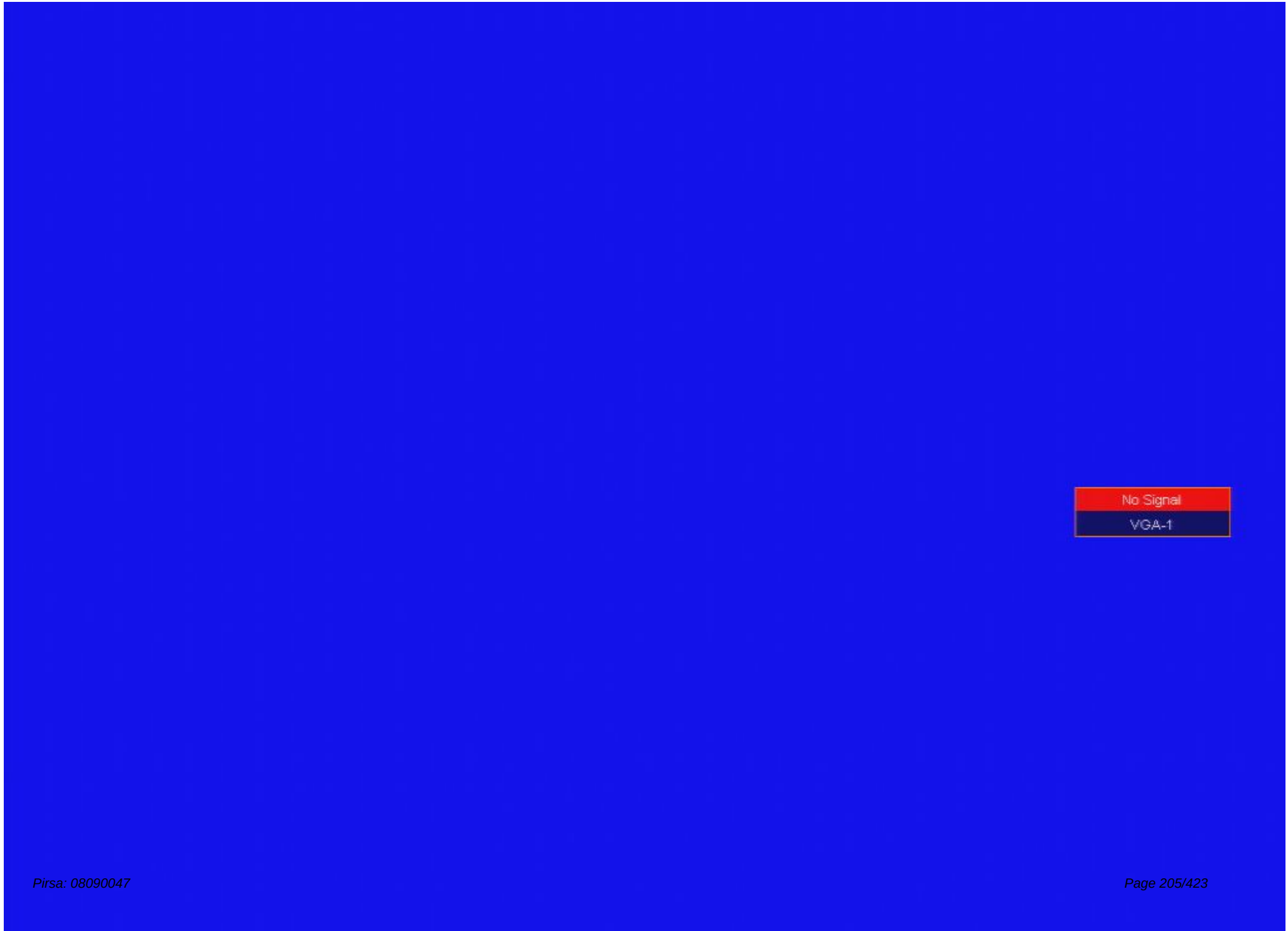

No Signal
VGA-1

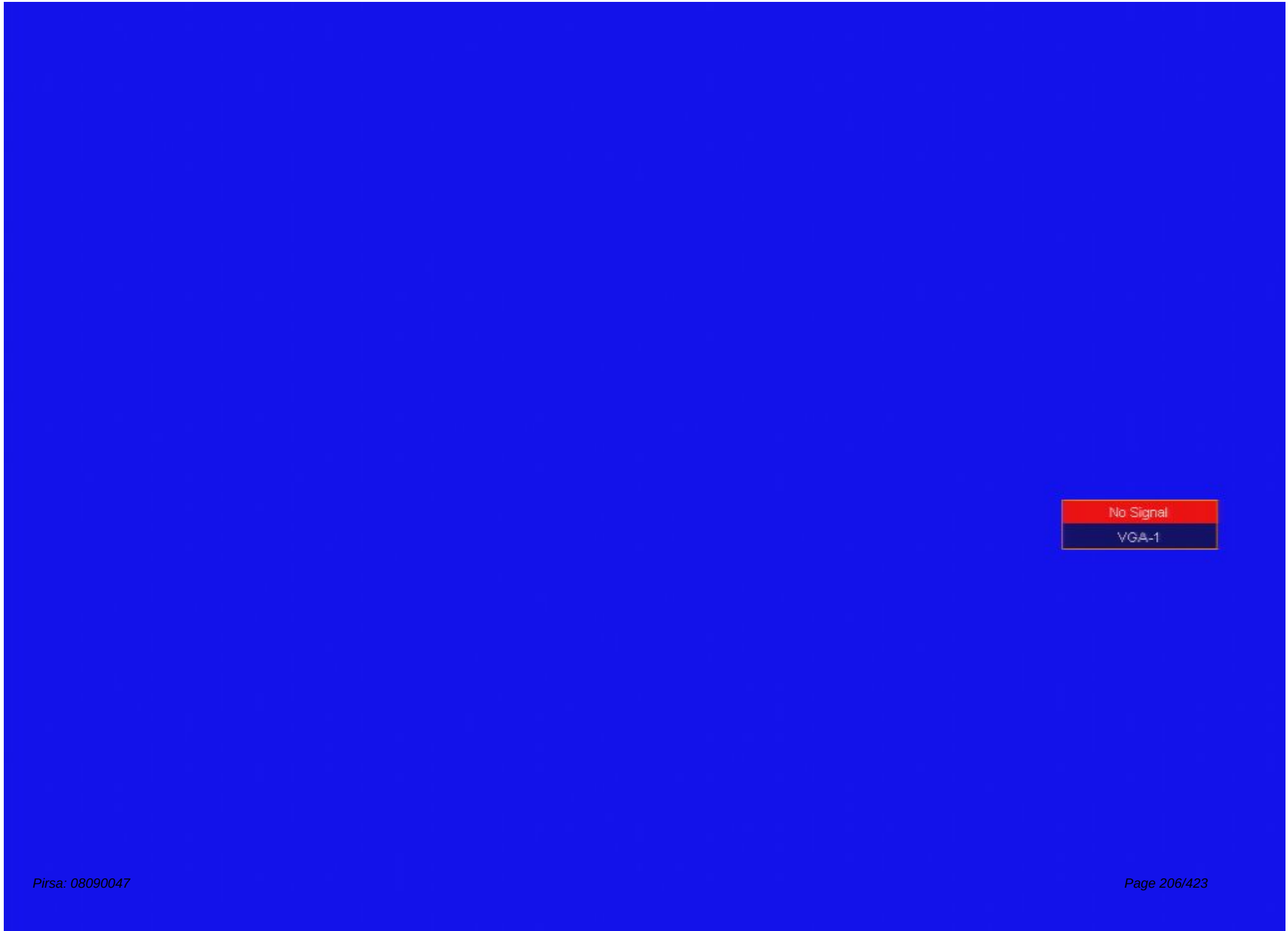

No Signal
VGA-1

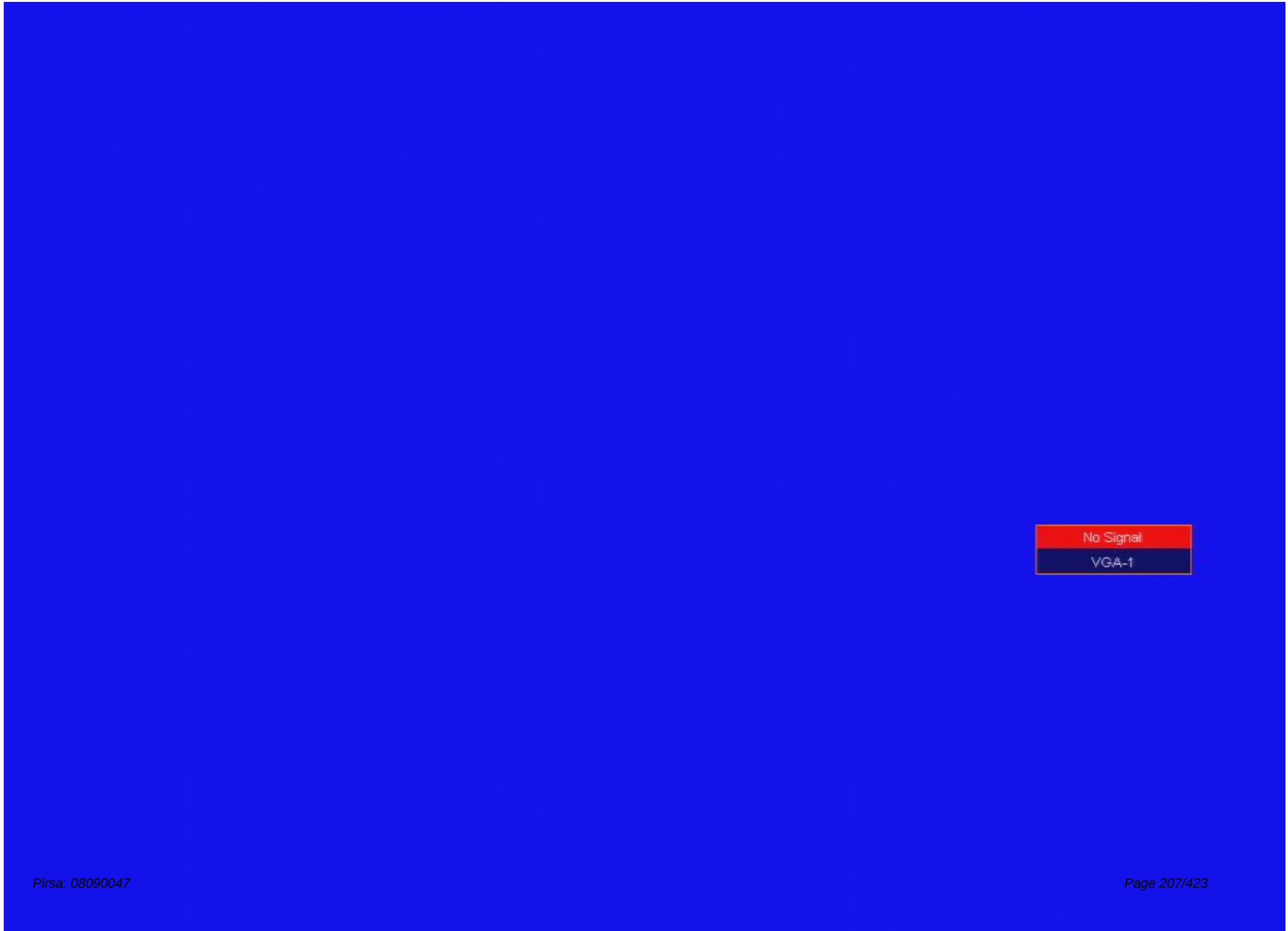

No Signal
VGA-1

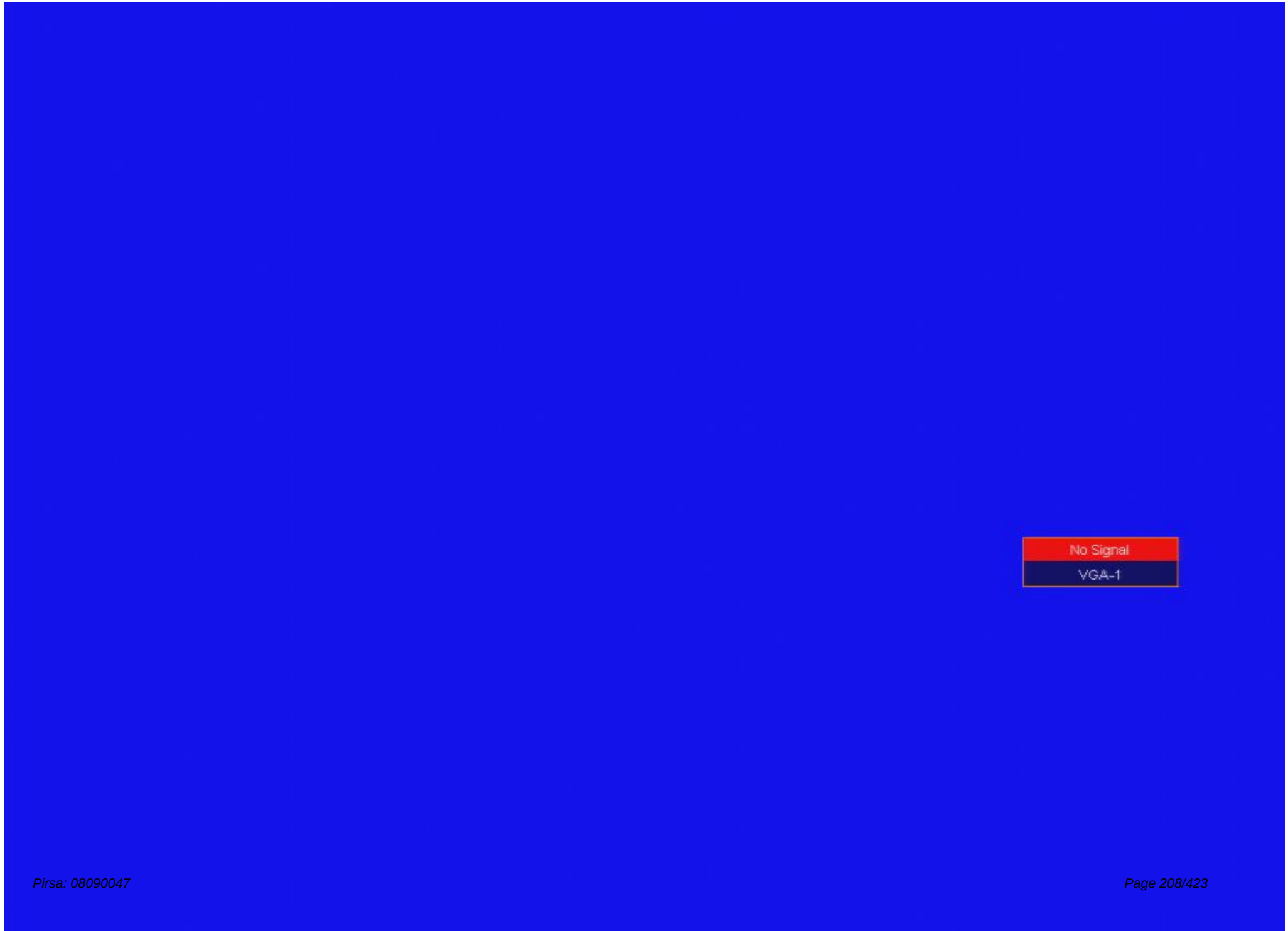

No Signal
VGA-1

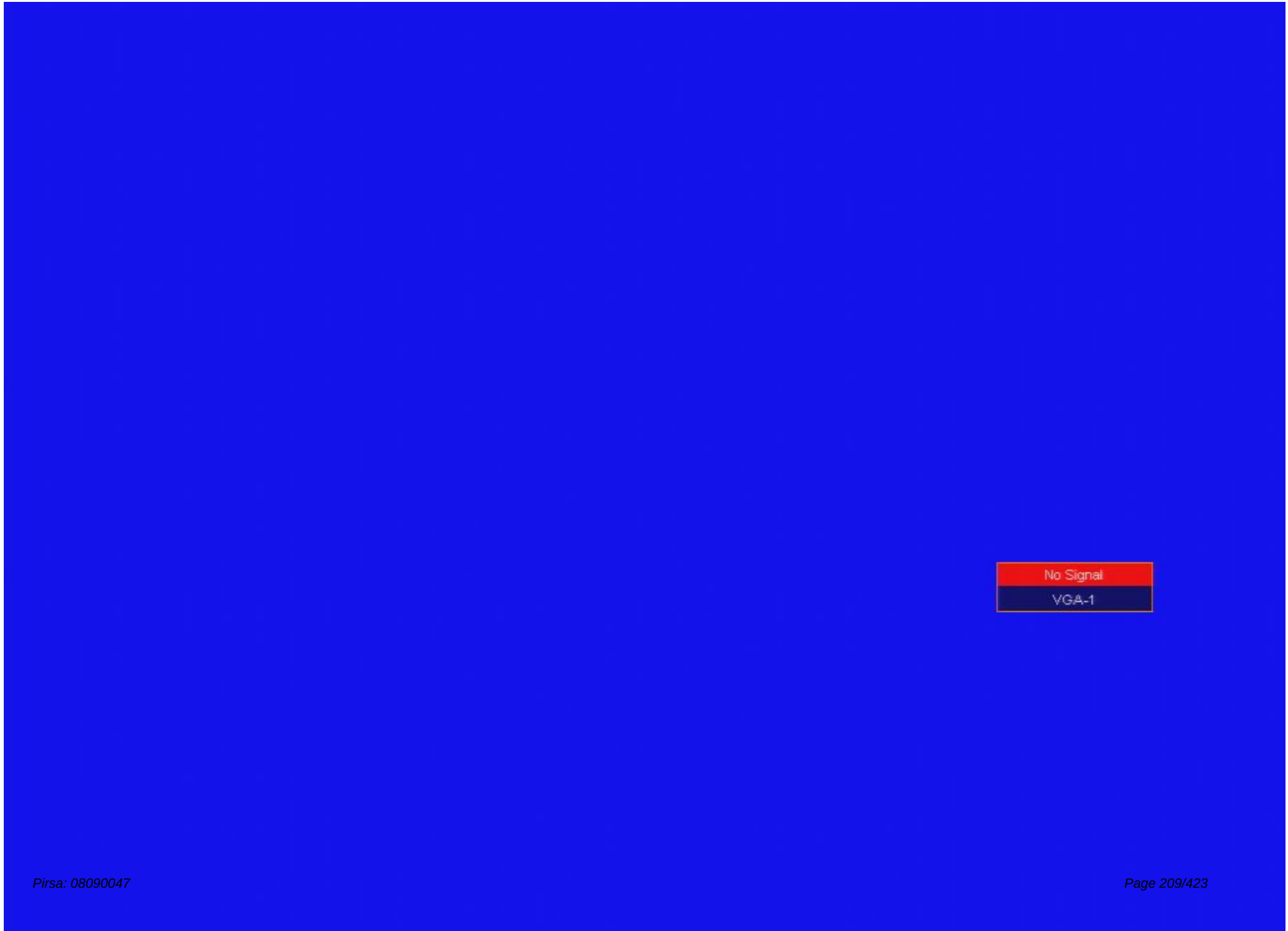

No Signal
VGA-1

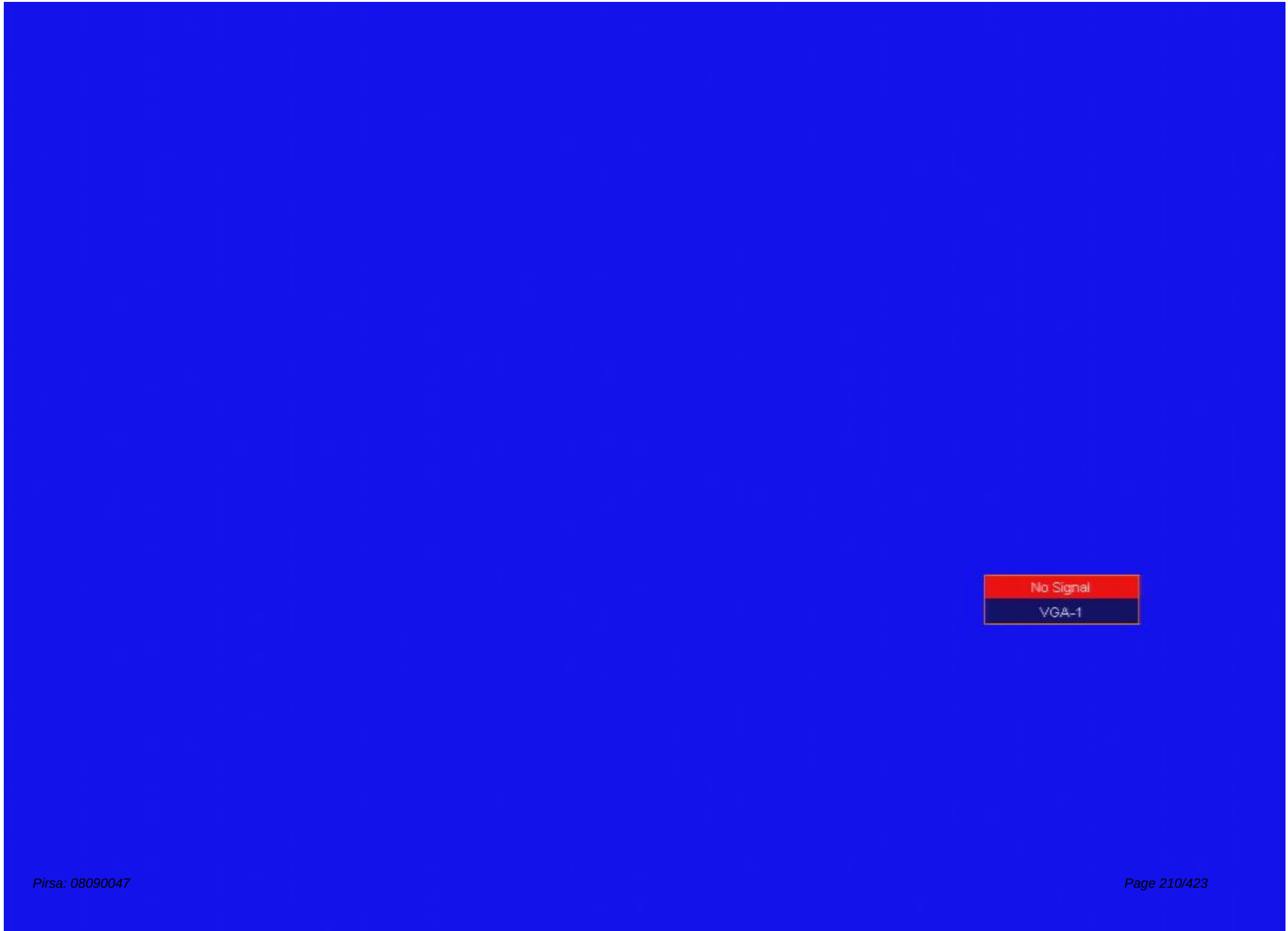

No Signal
VGA-1

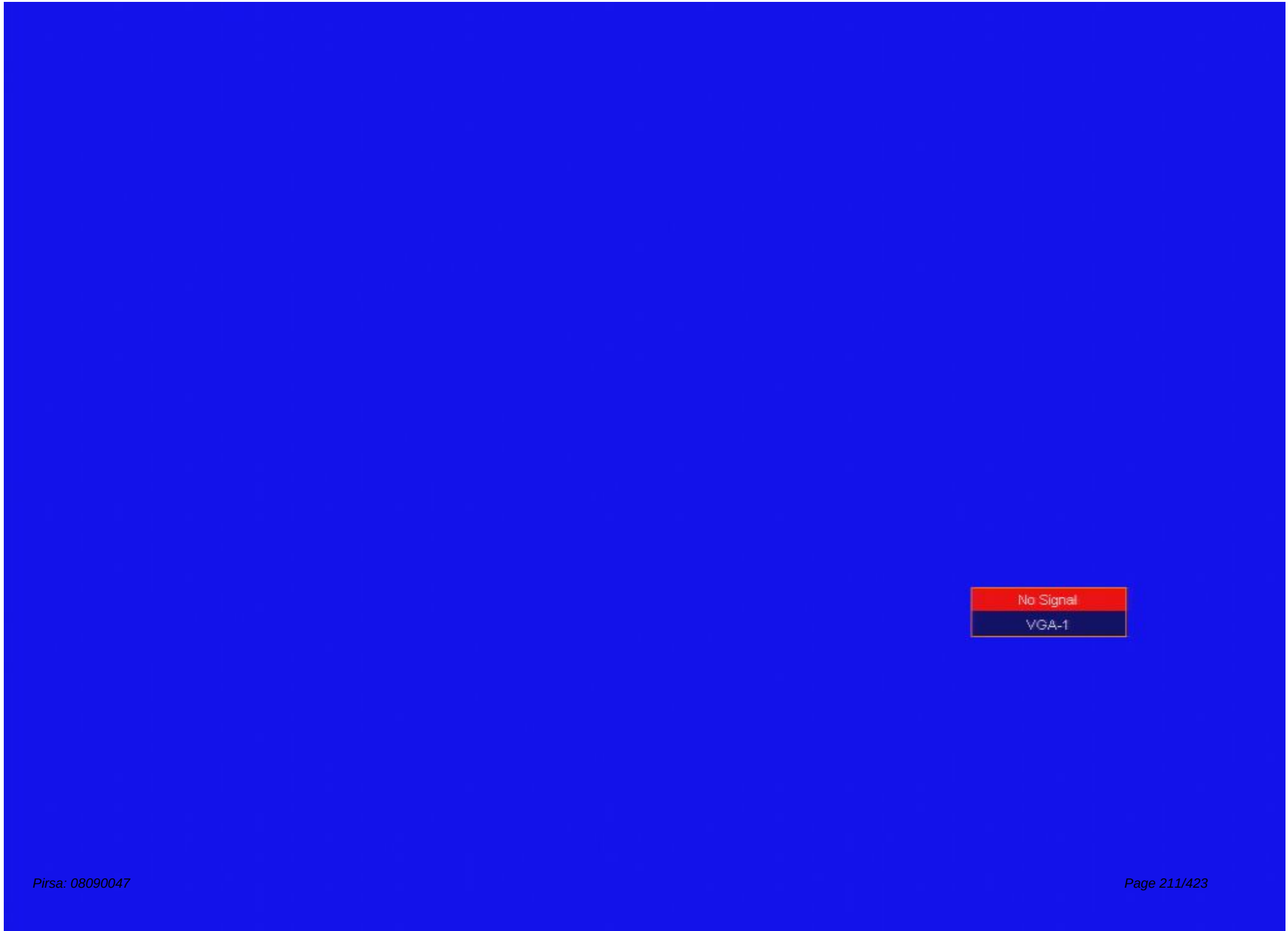

No Signal
VGA-1

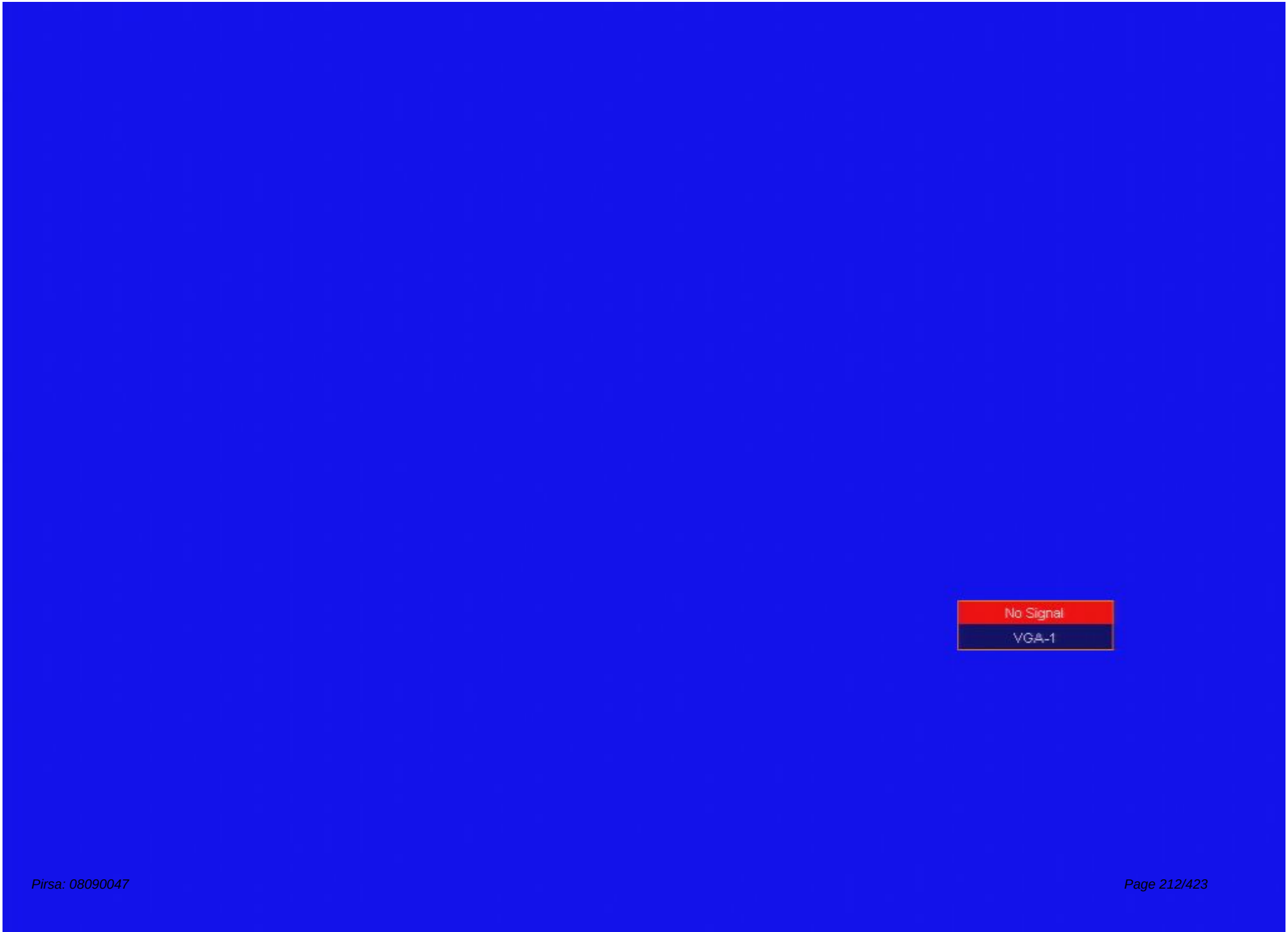

No Signal
VGA-1

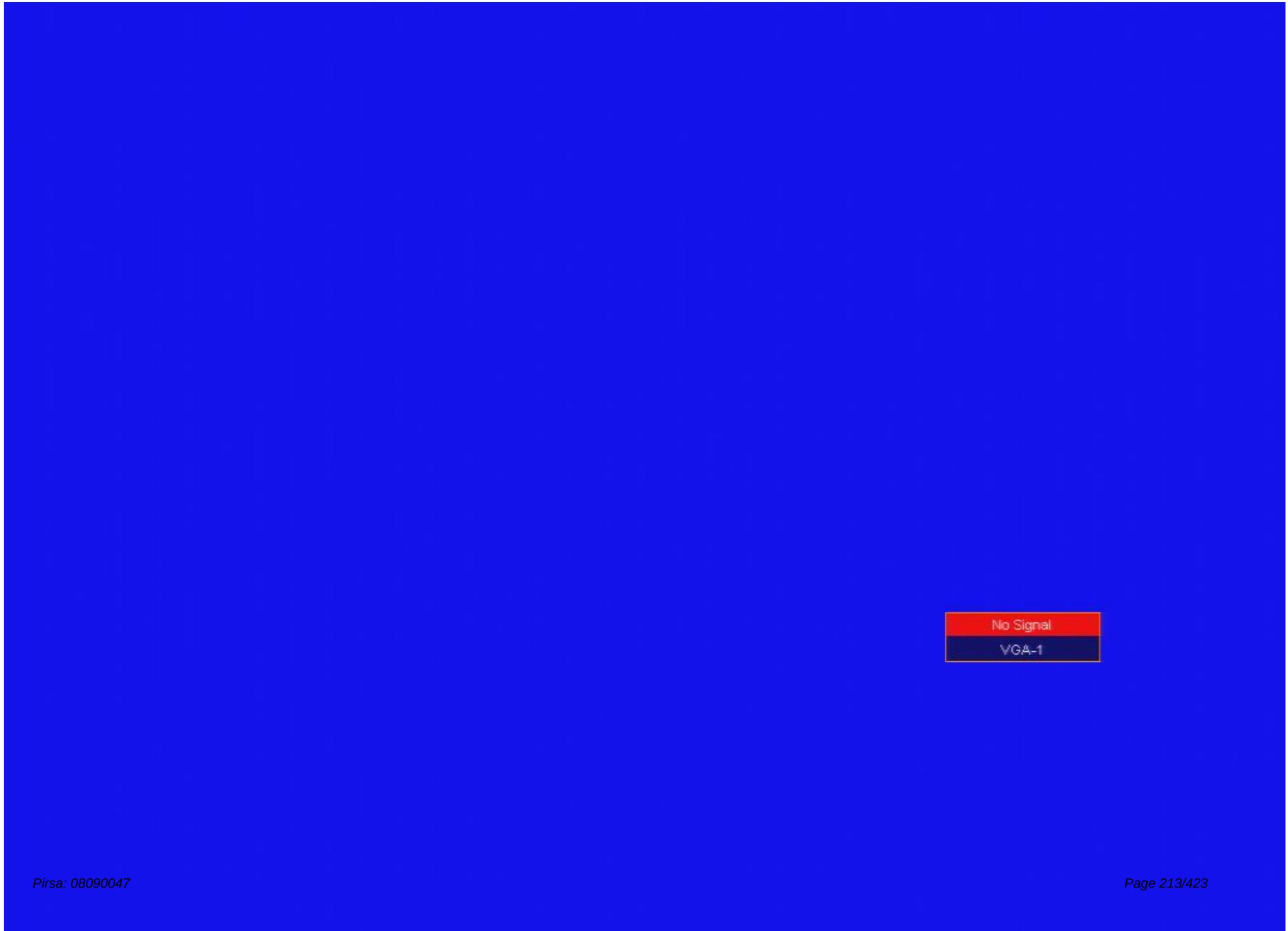

No Signal
VGA-1

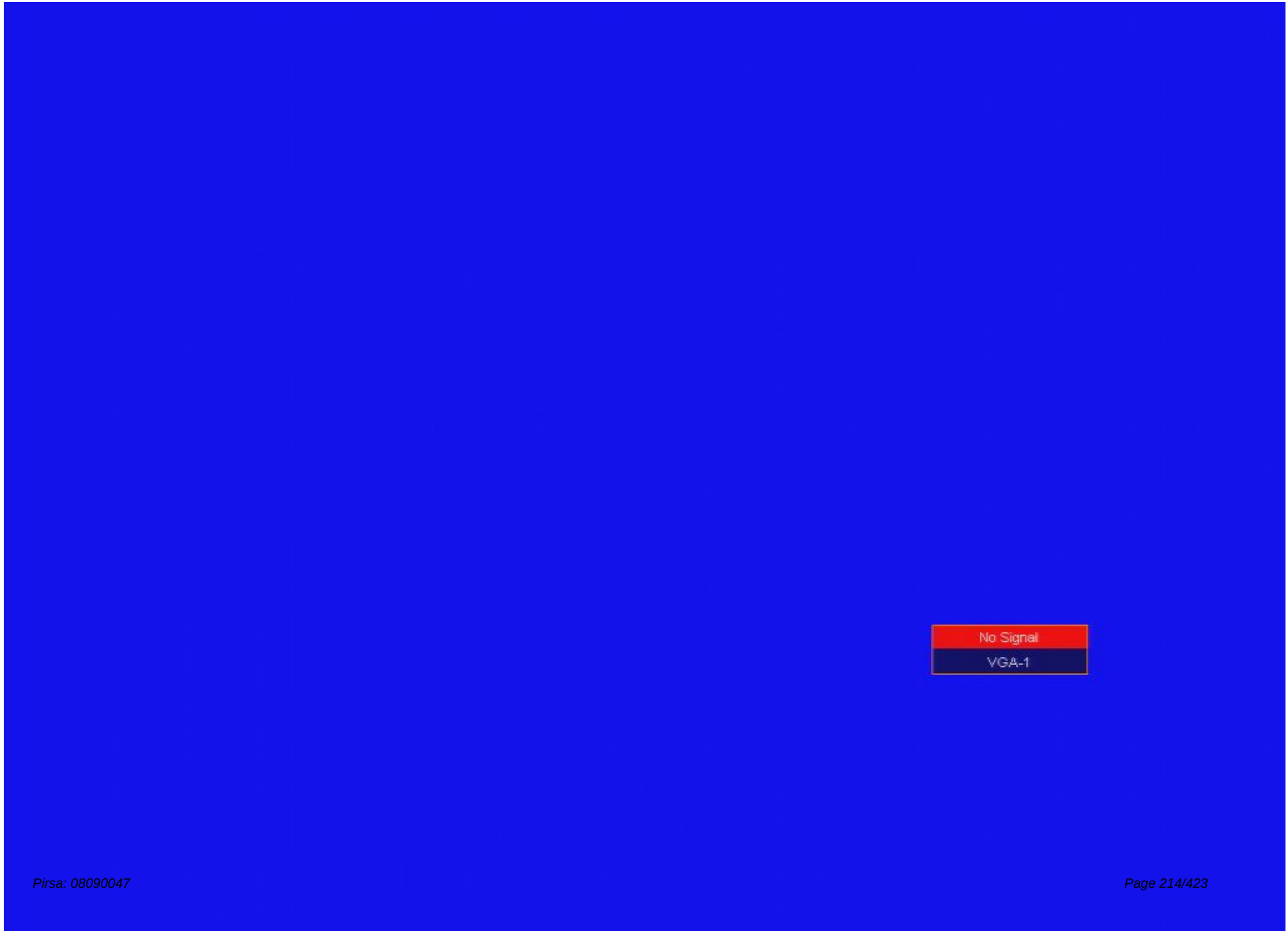

No Signal
VGA-1

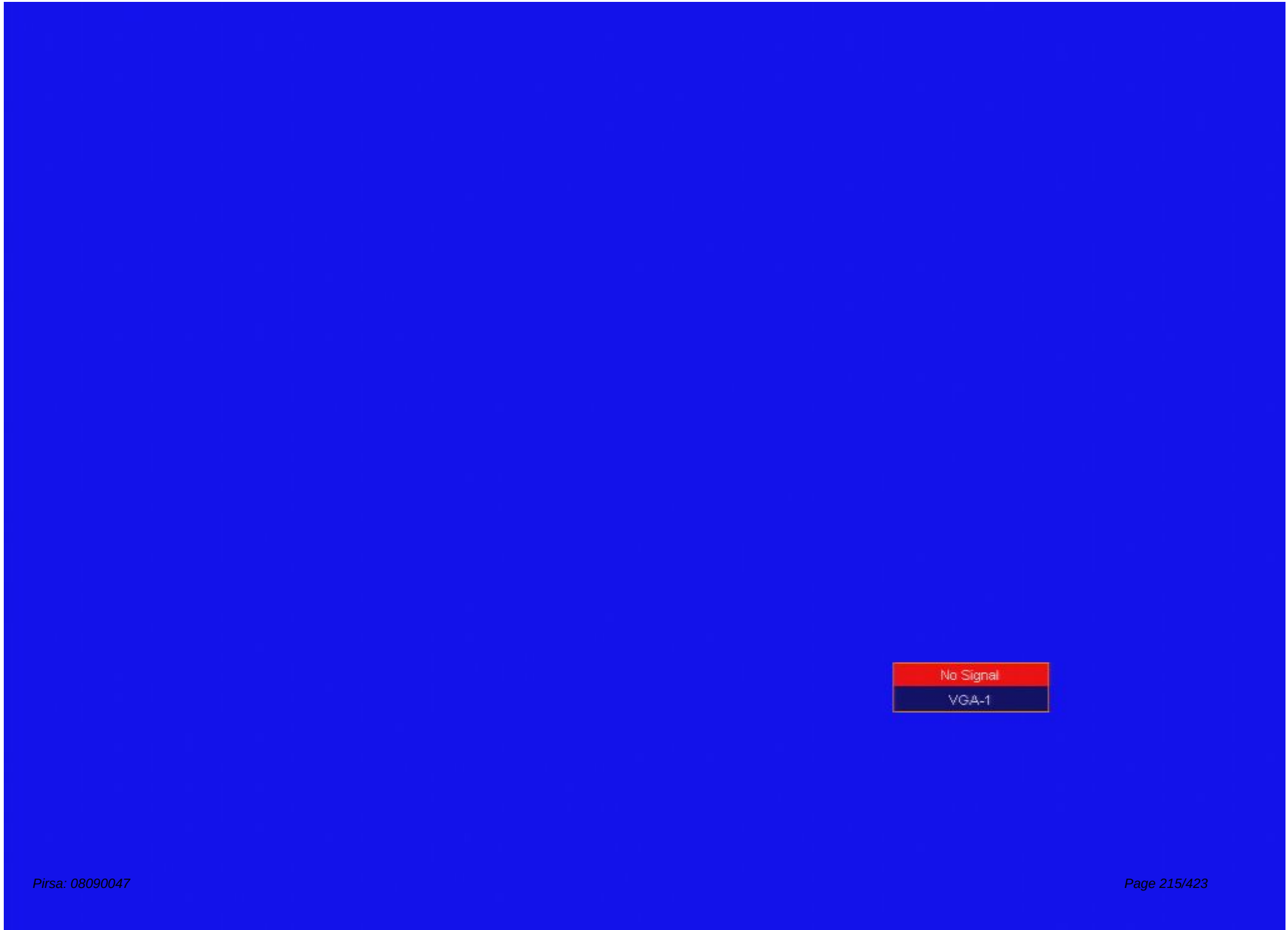

No Signal
VGA-1

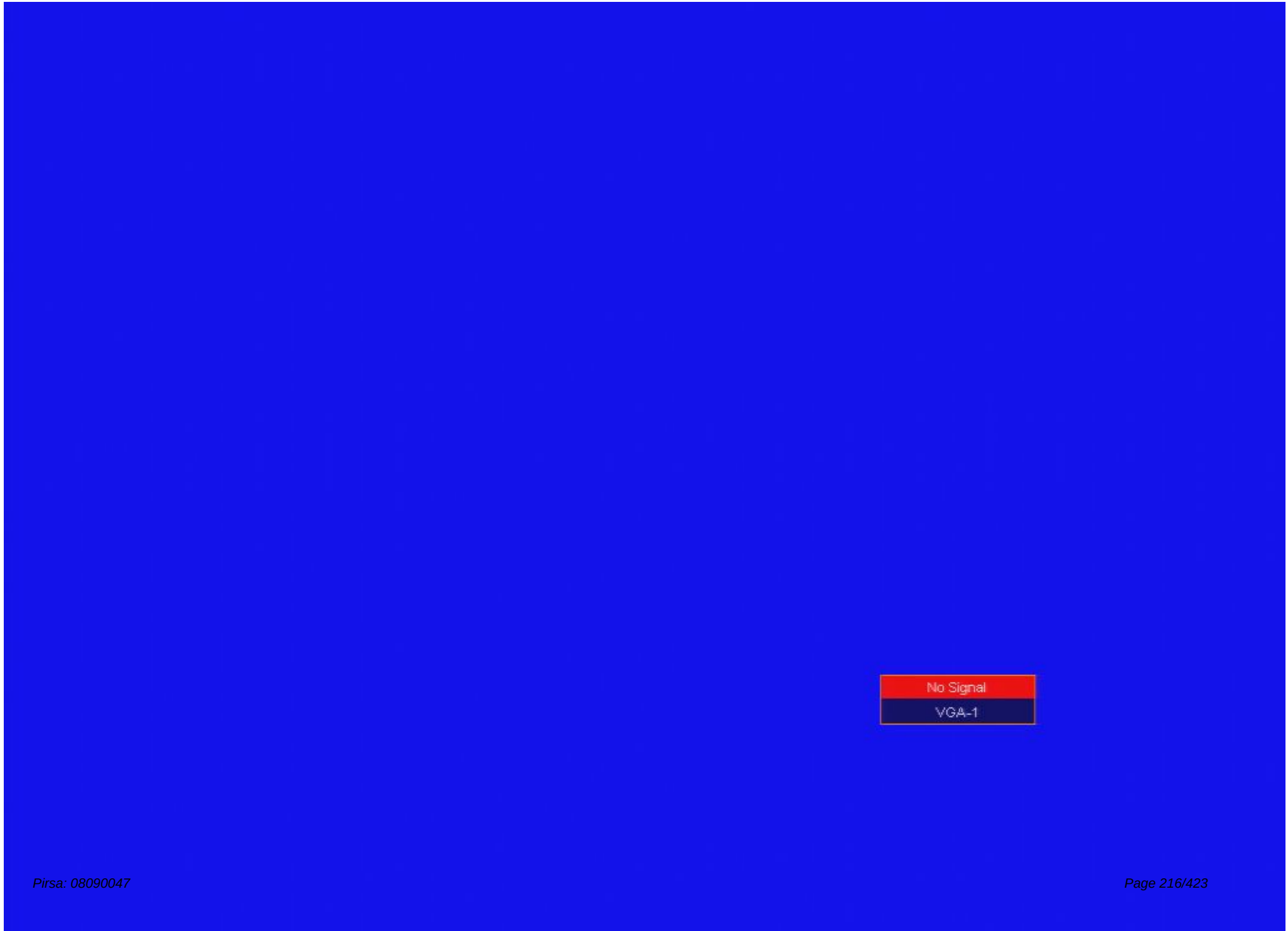

No Signal
VGA-1

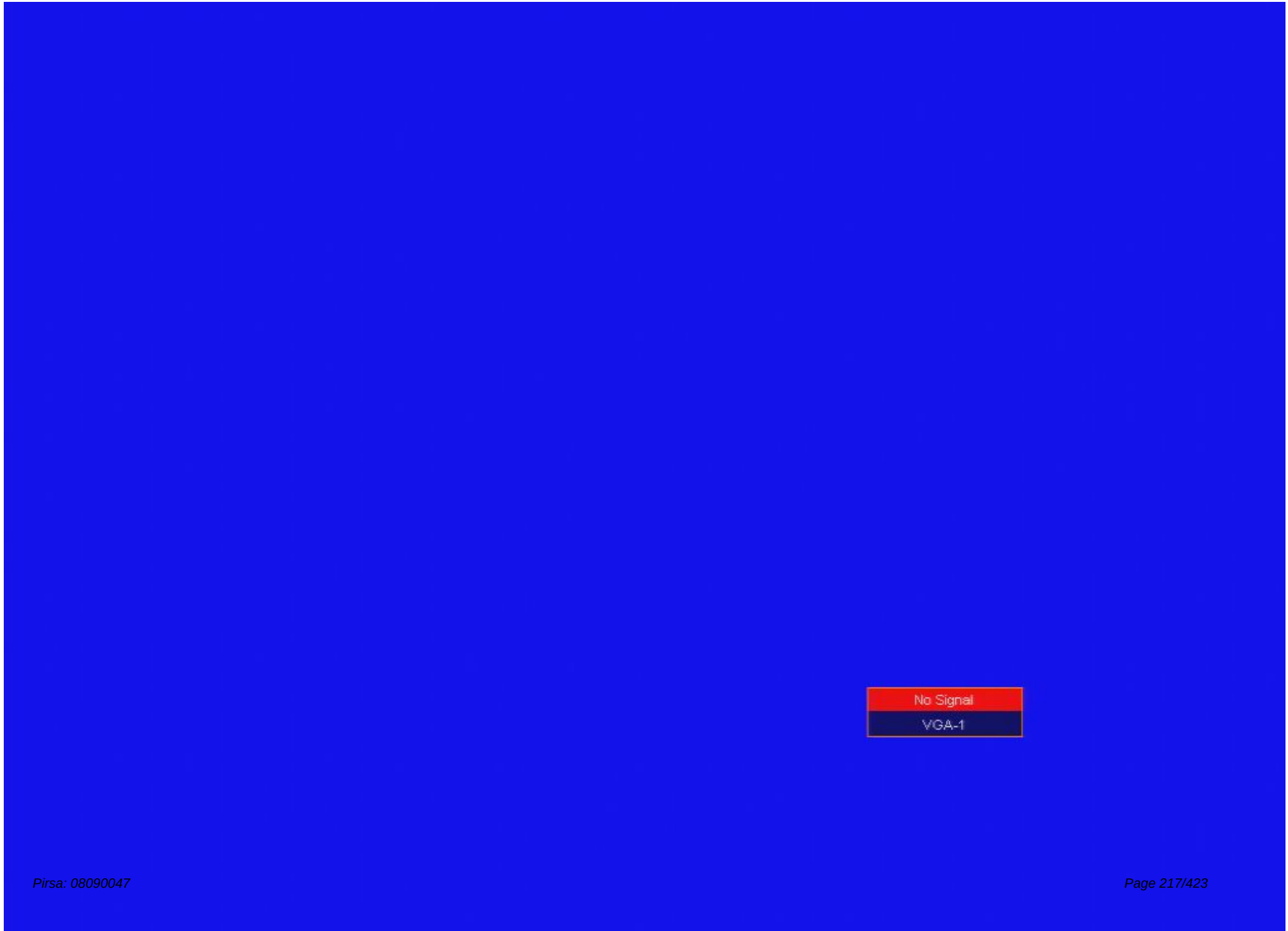

No Signal
VGA-1

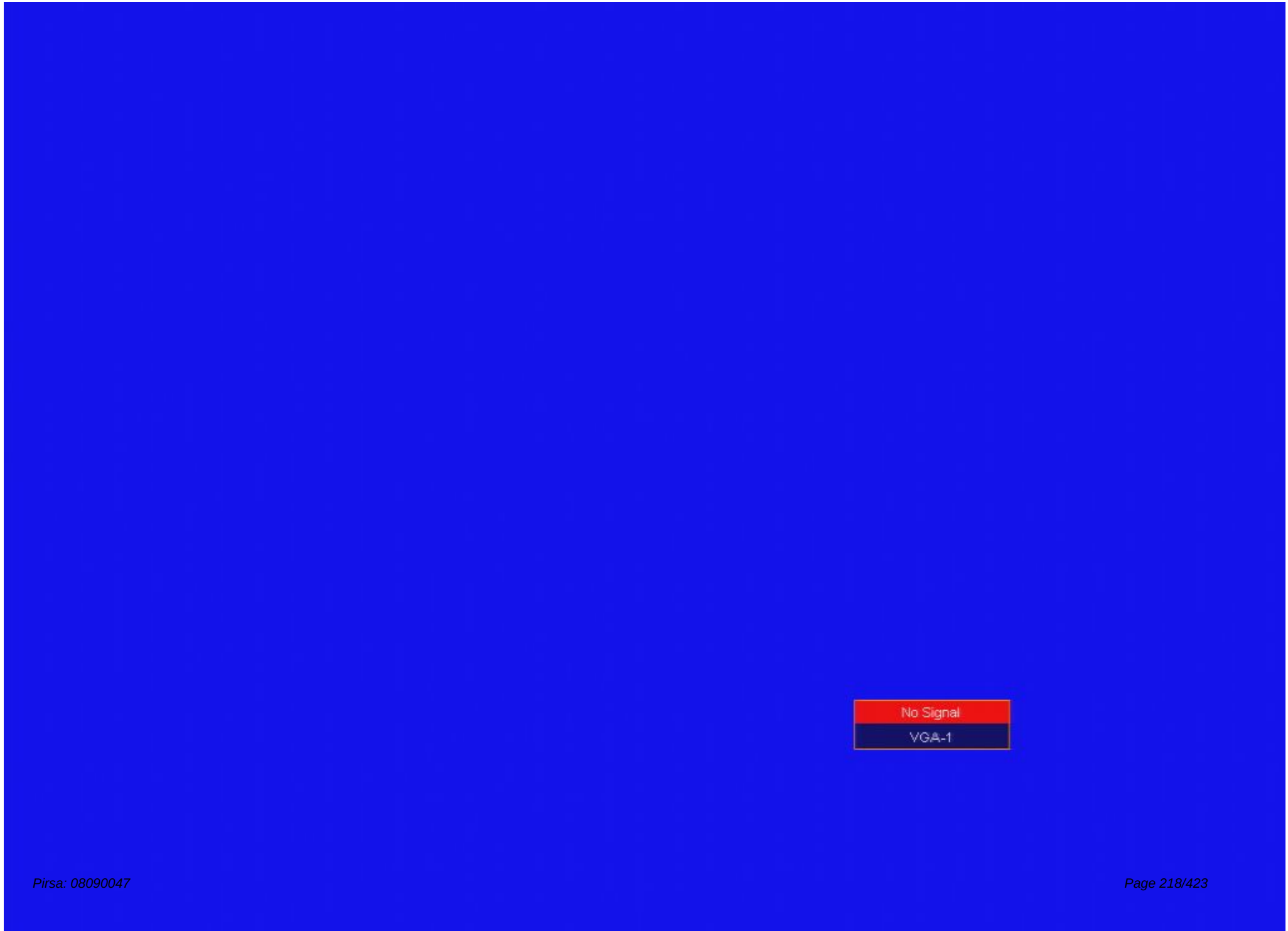

No Signal
VGA-1

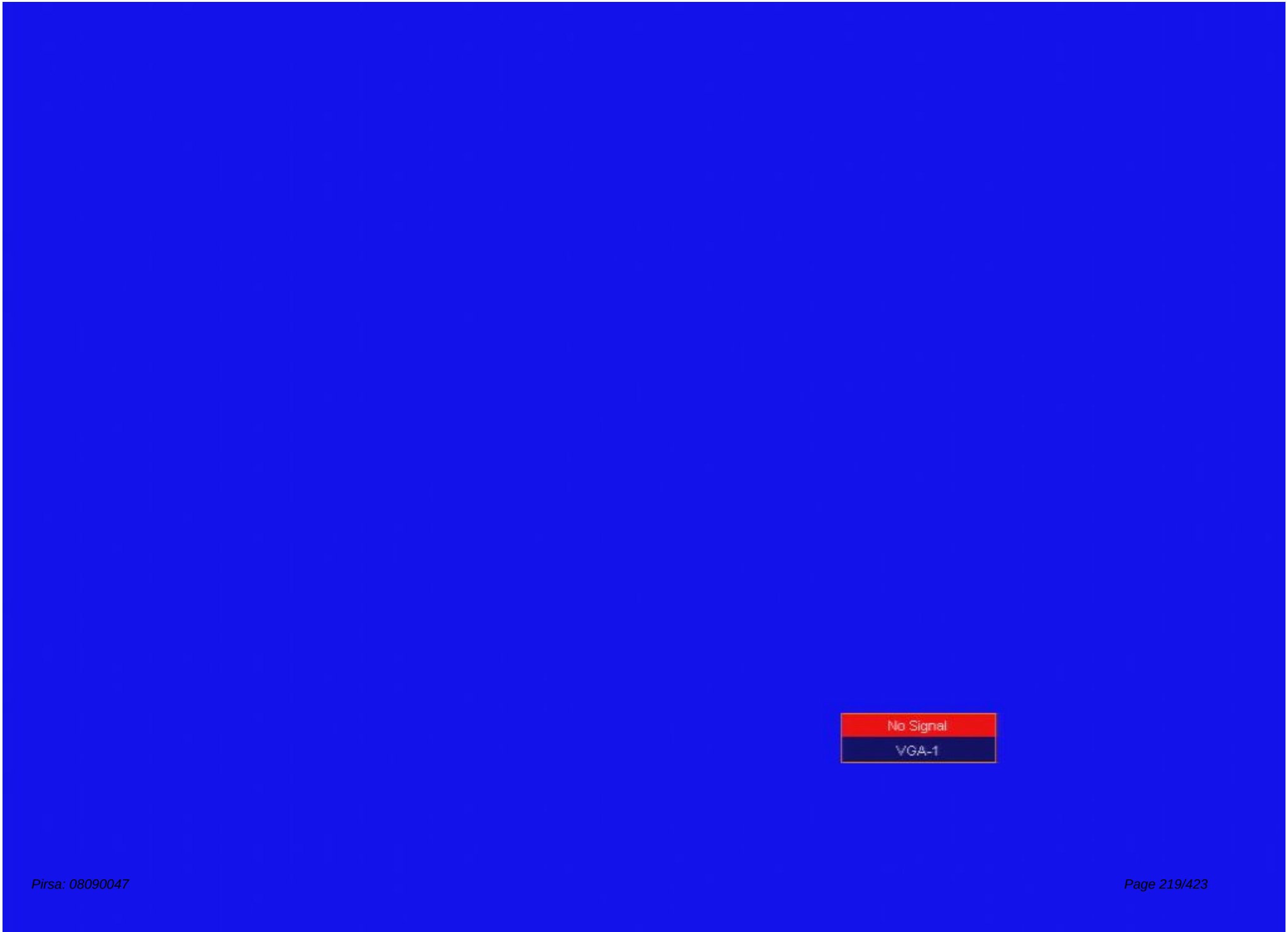

No Signal
VGA-1

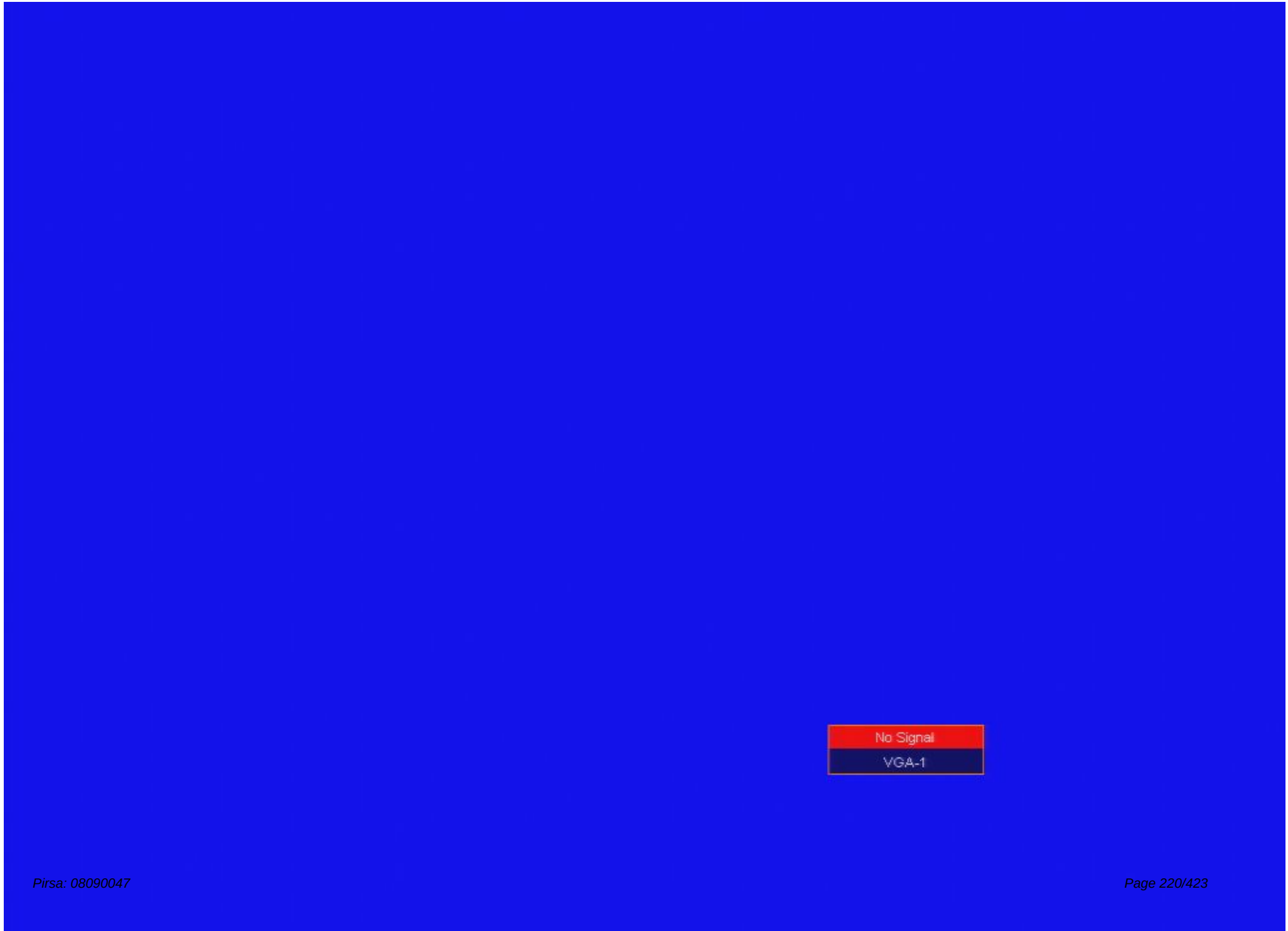

No Signal
VGA-1

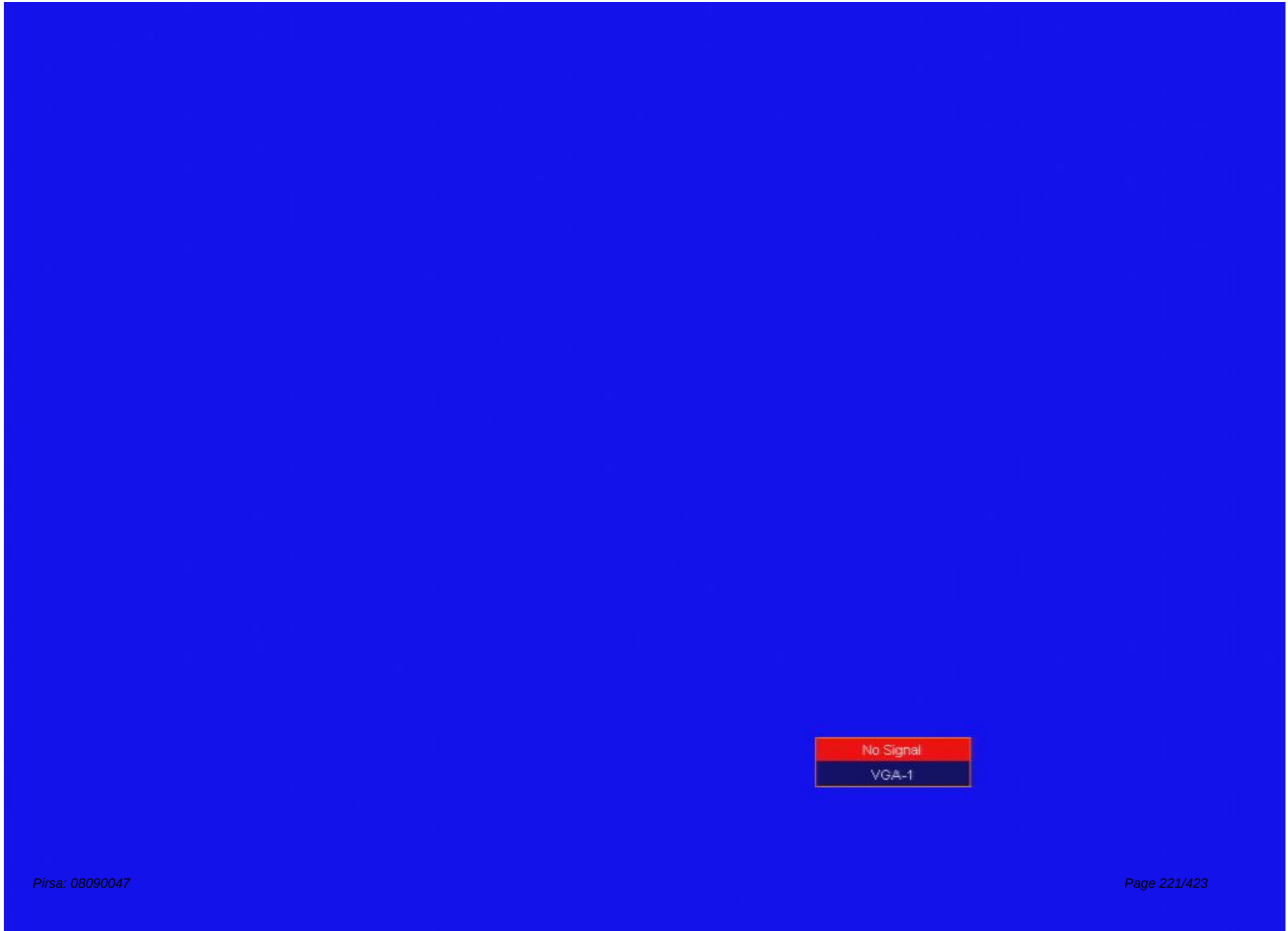

No Signal
VGA-1

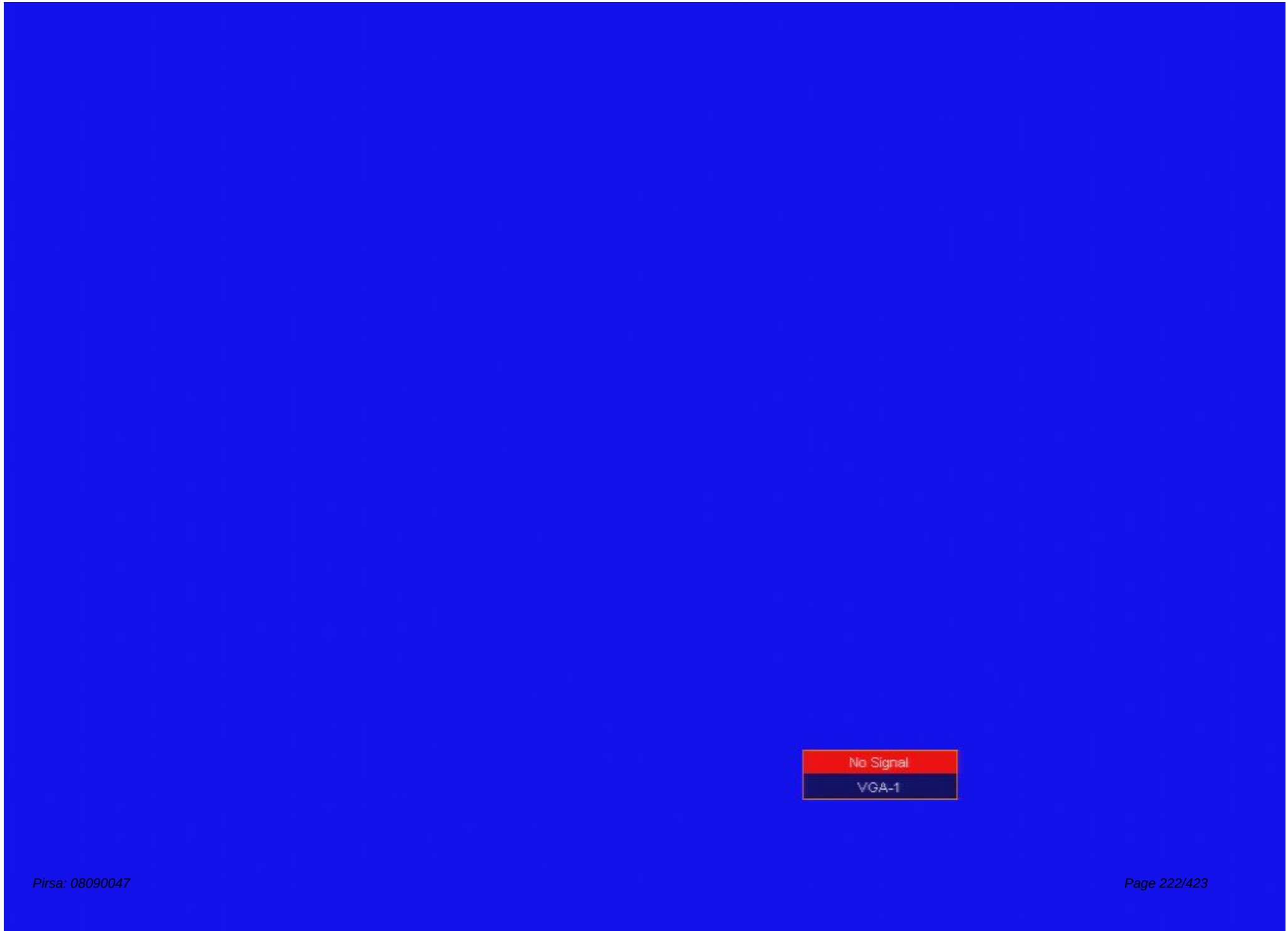

No Signal
VGA-1

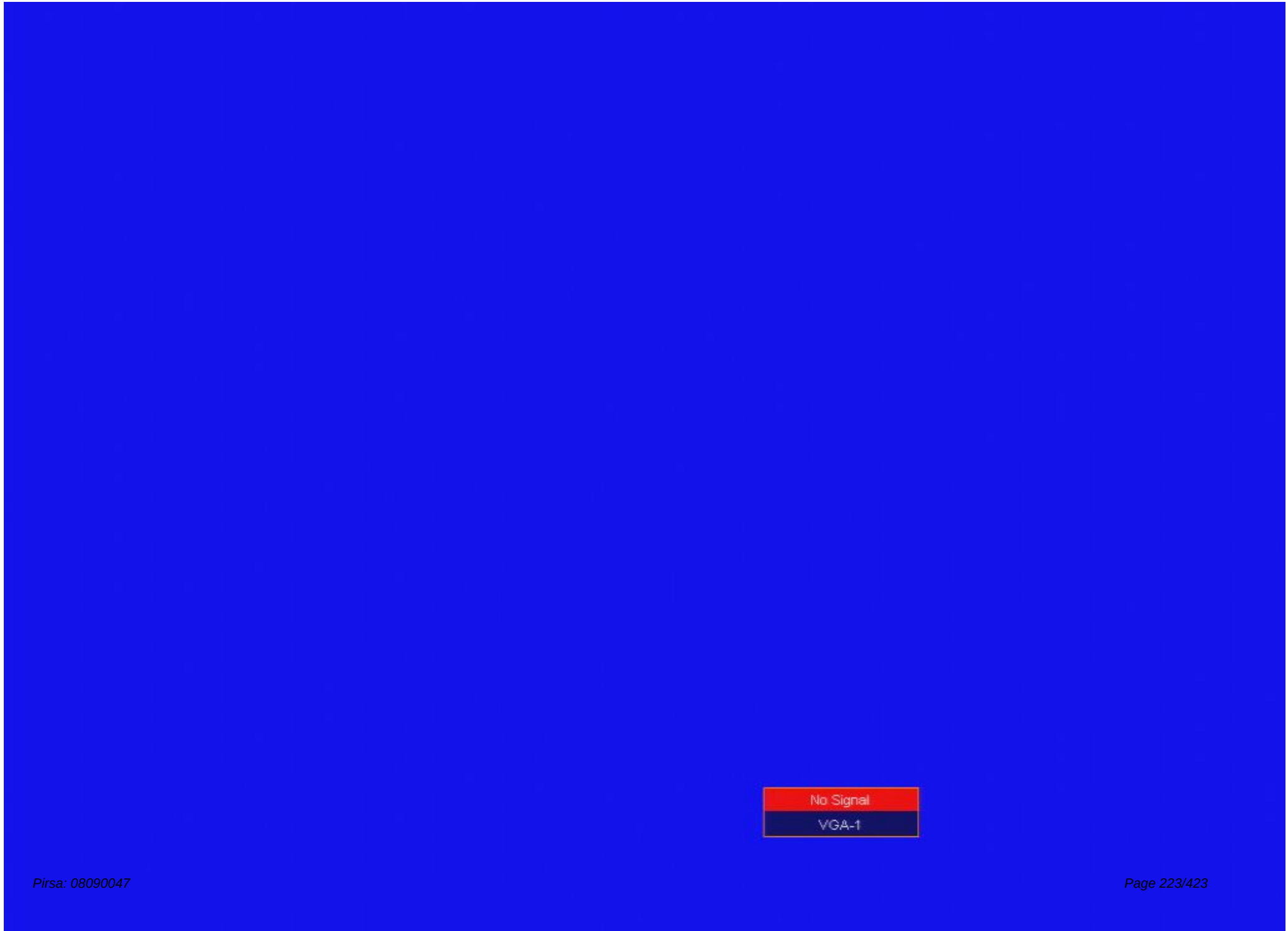

No Signal
VGA-1

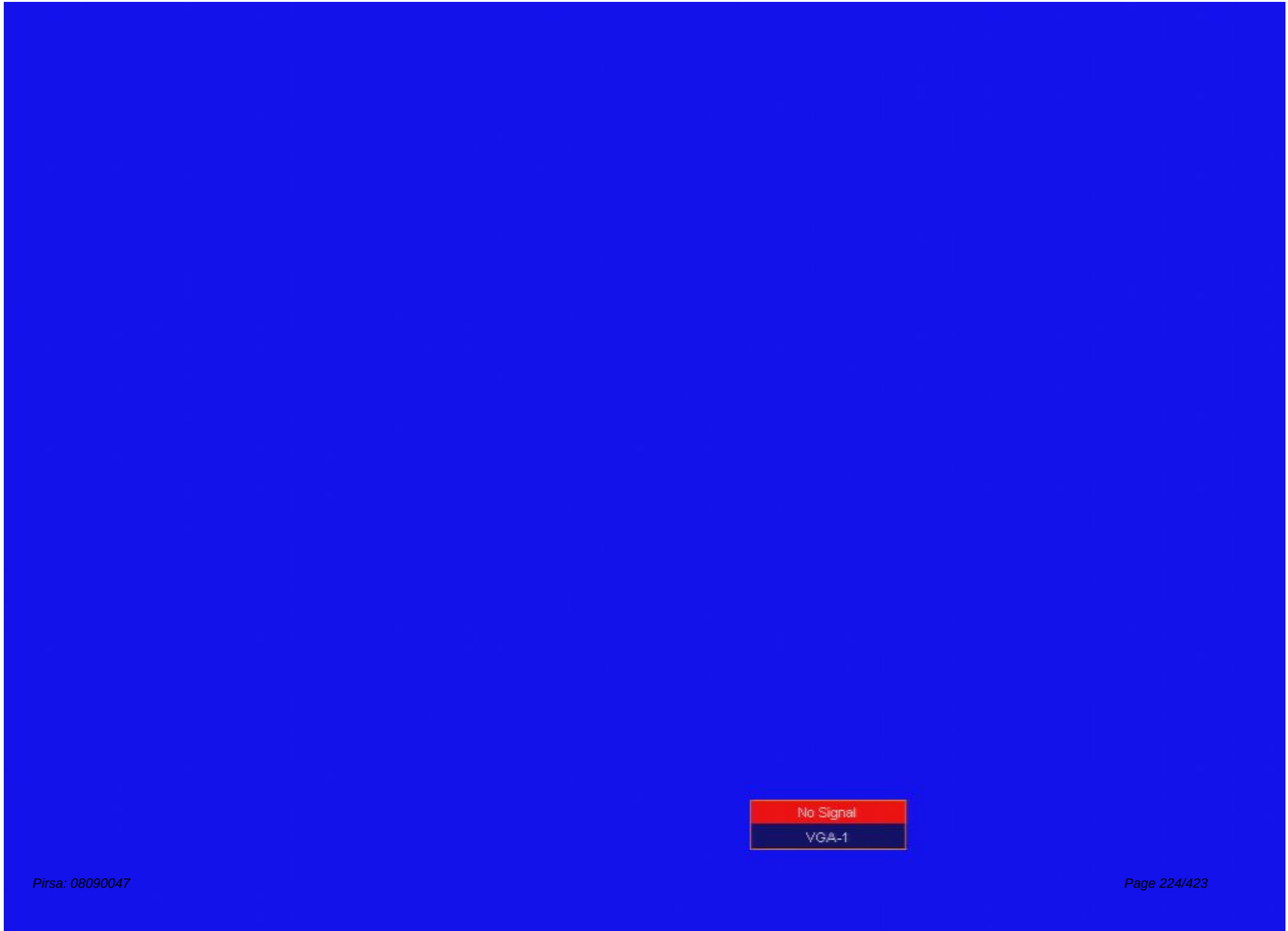

No Signal
VGA-1

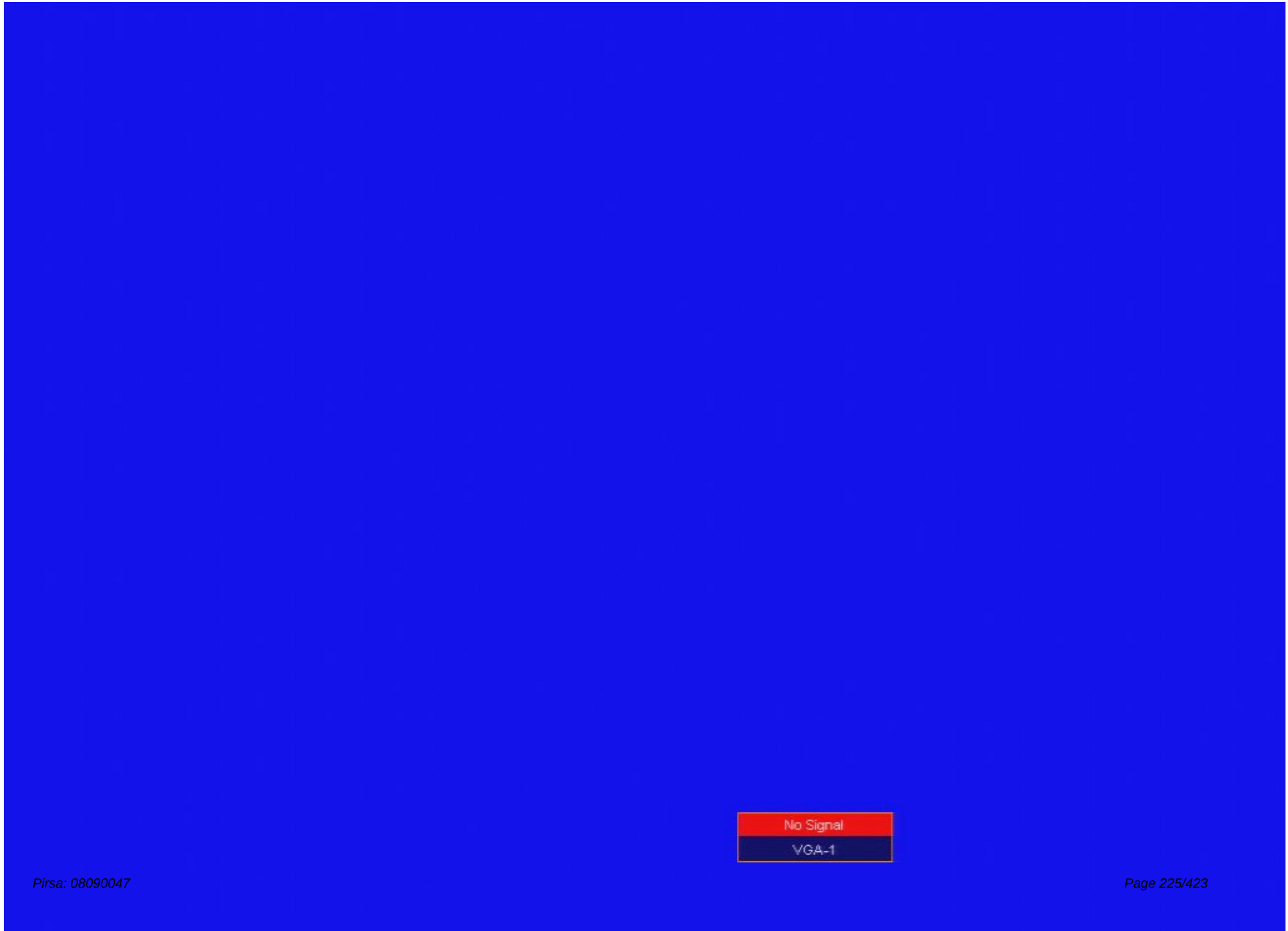

No Signal
VGA-1

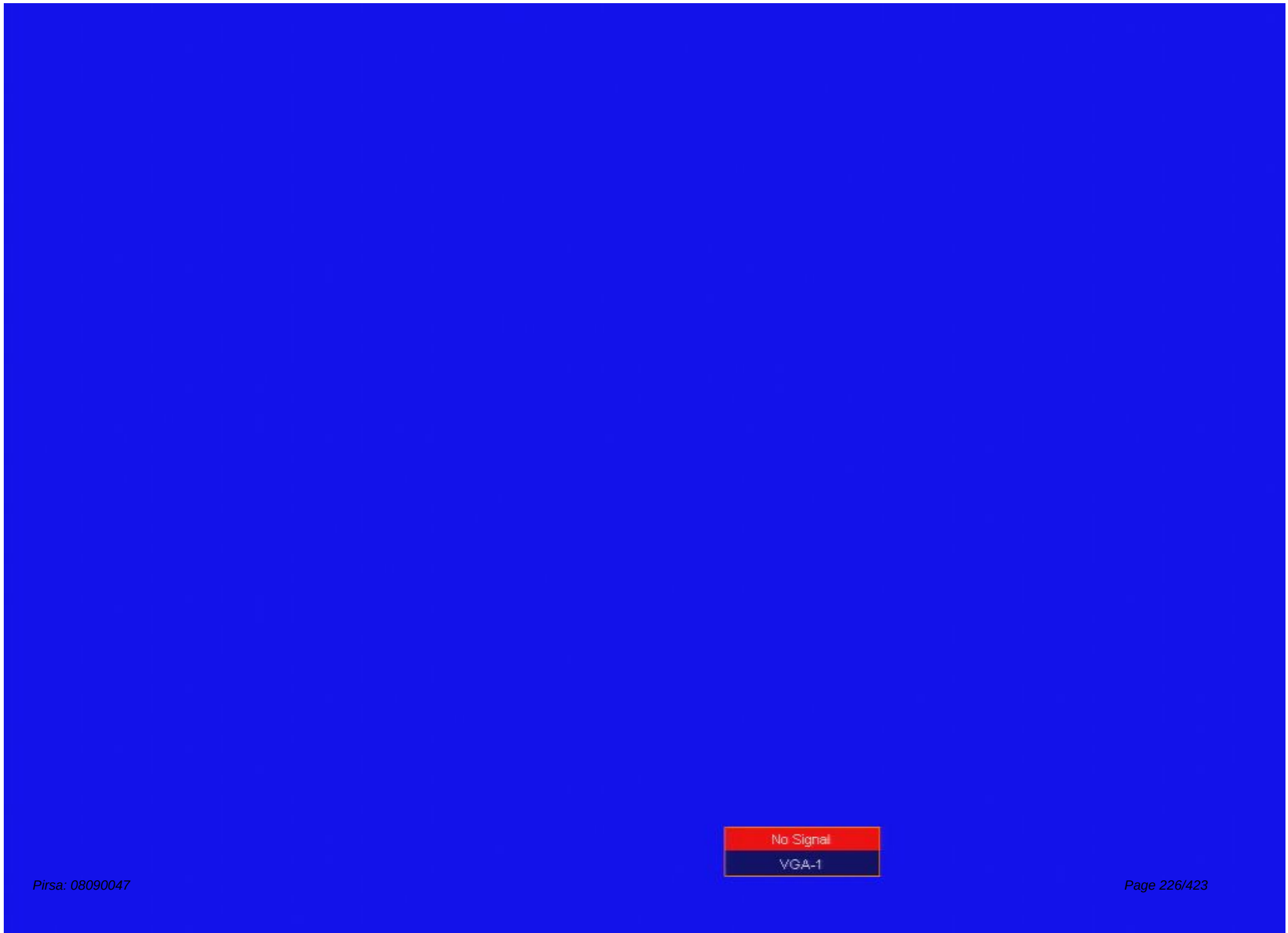

No Signal
VGA-1


No Signal
VGA-1

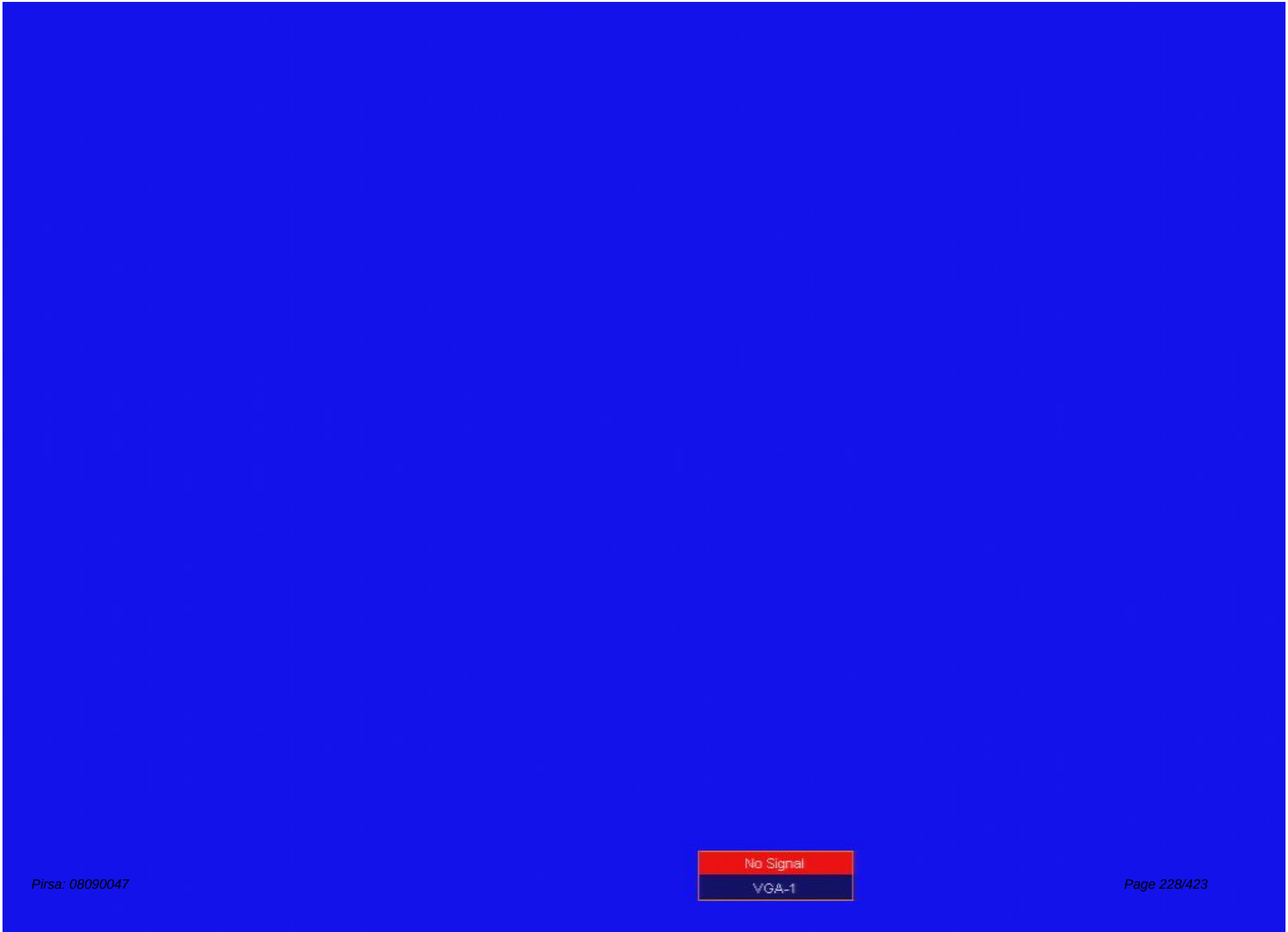

No Signal
VGA-1

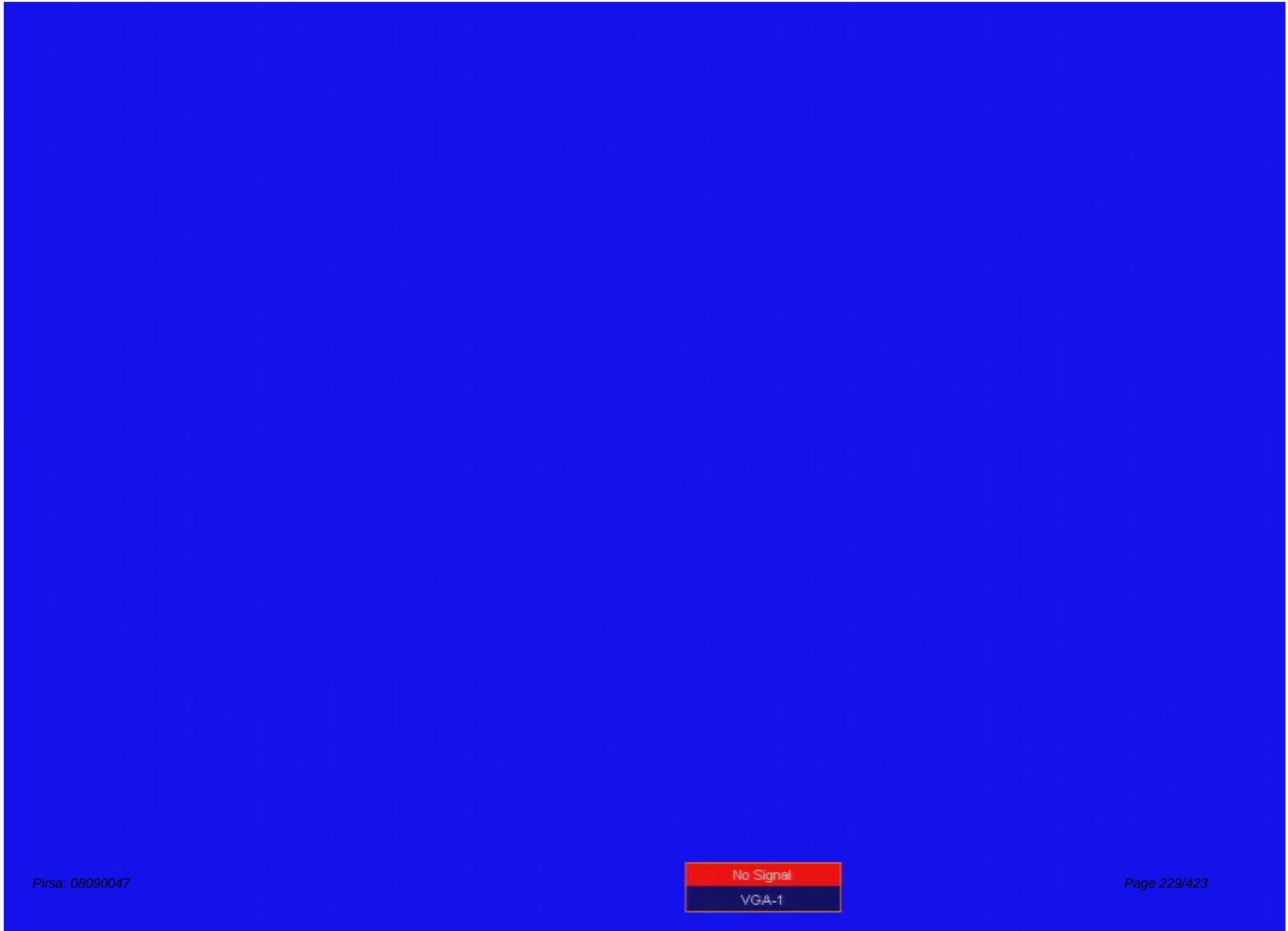

No Signal
VGA-1

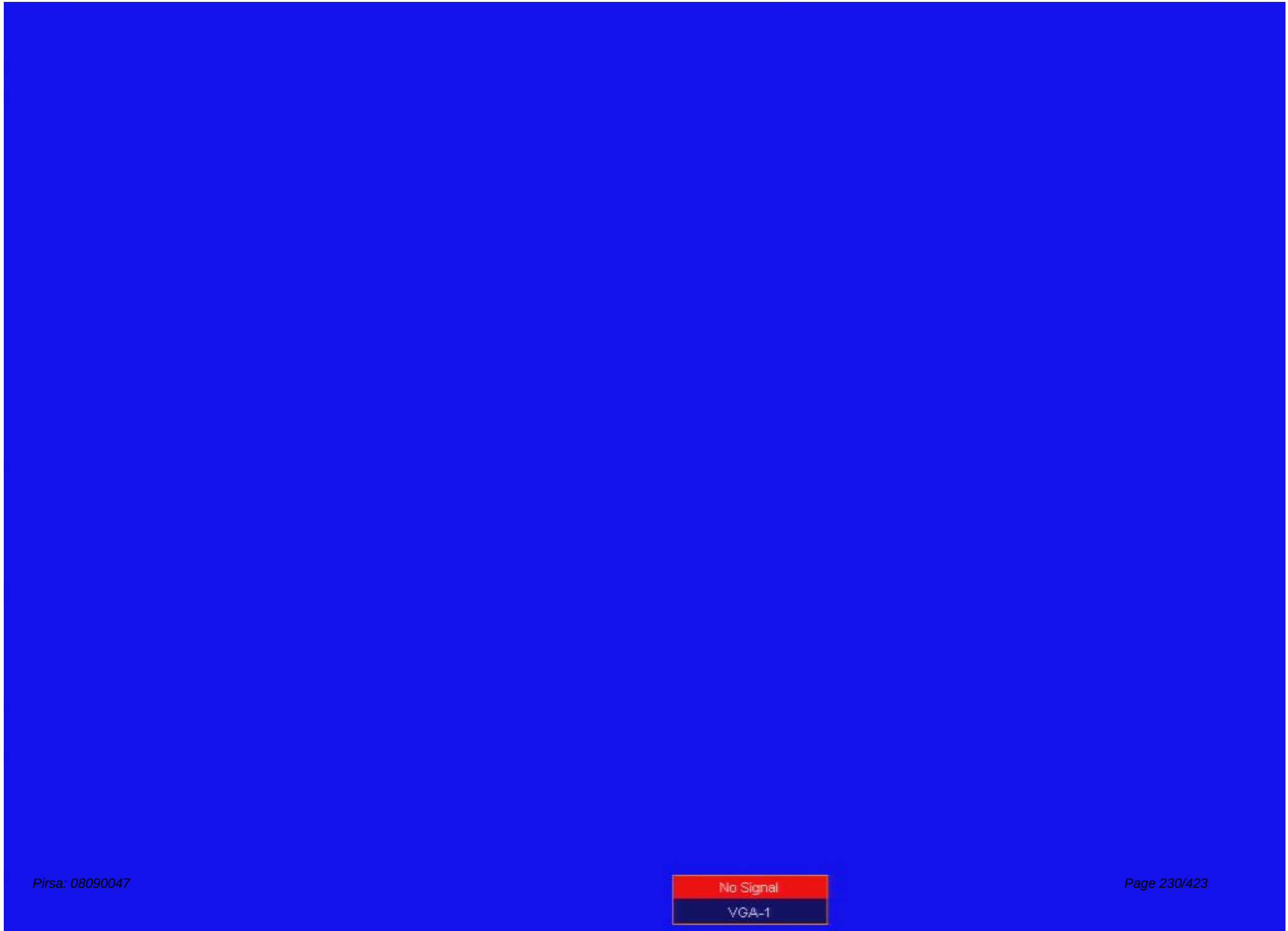

No Signal
VGA-1


No Signal
VGA-1

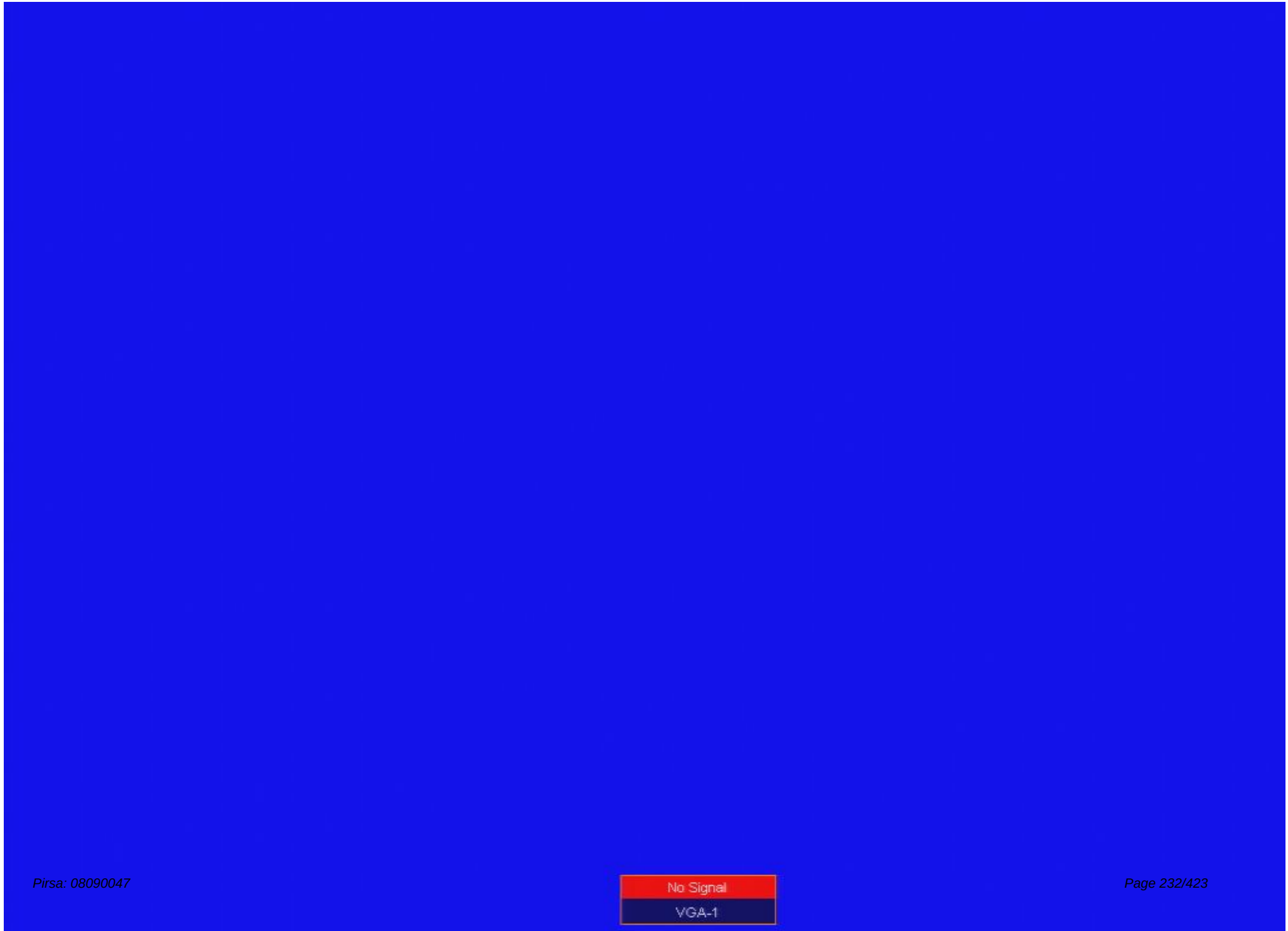

No Signal
VGA-1

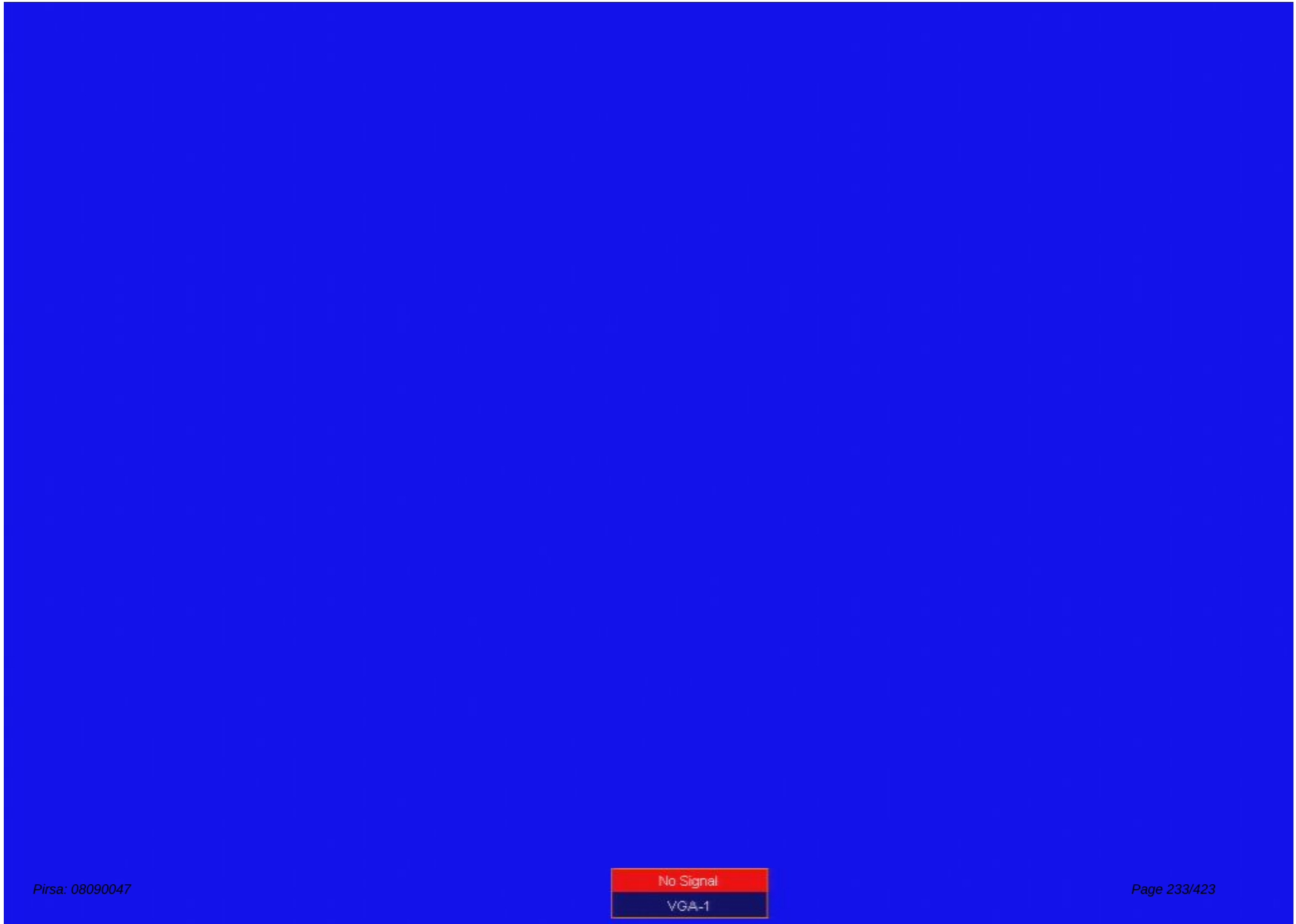

No Signal
VGA-1

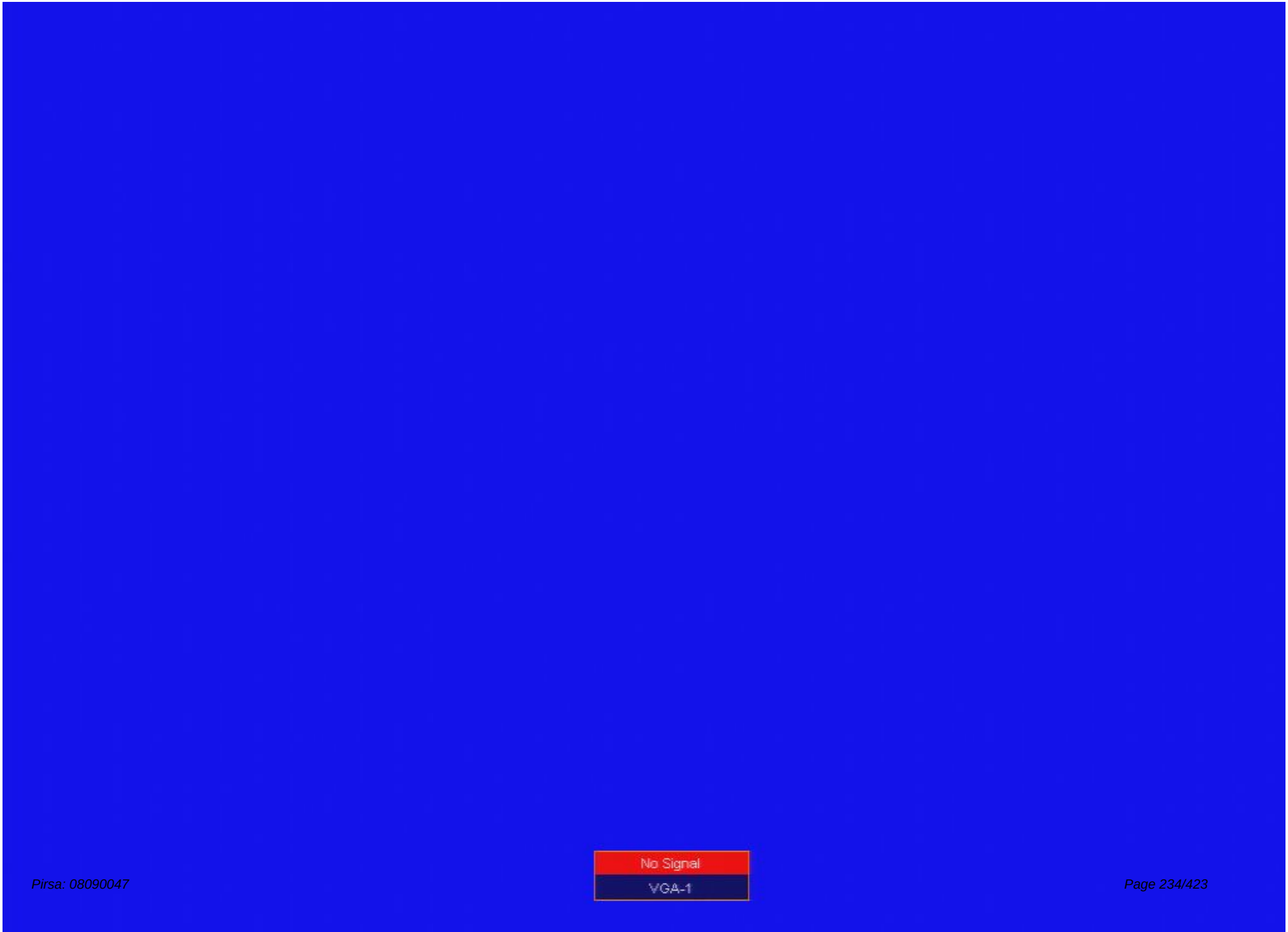

No Signal
VGA-1

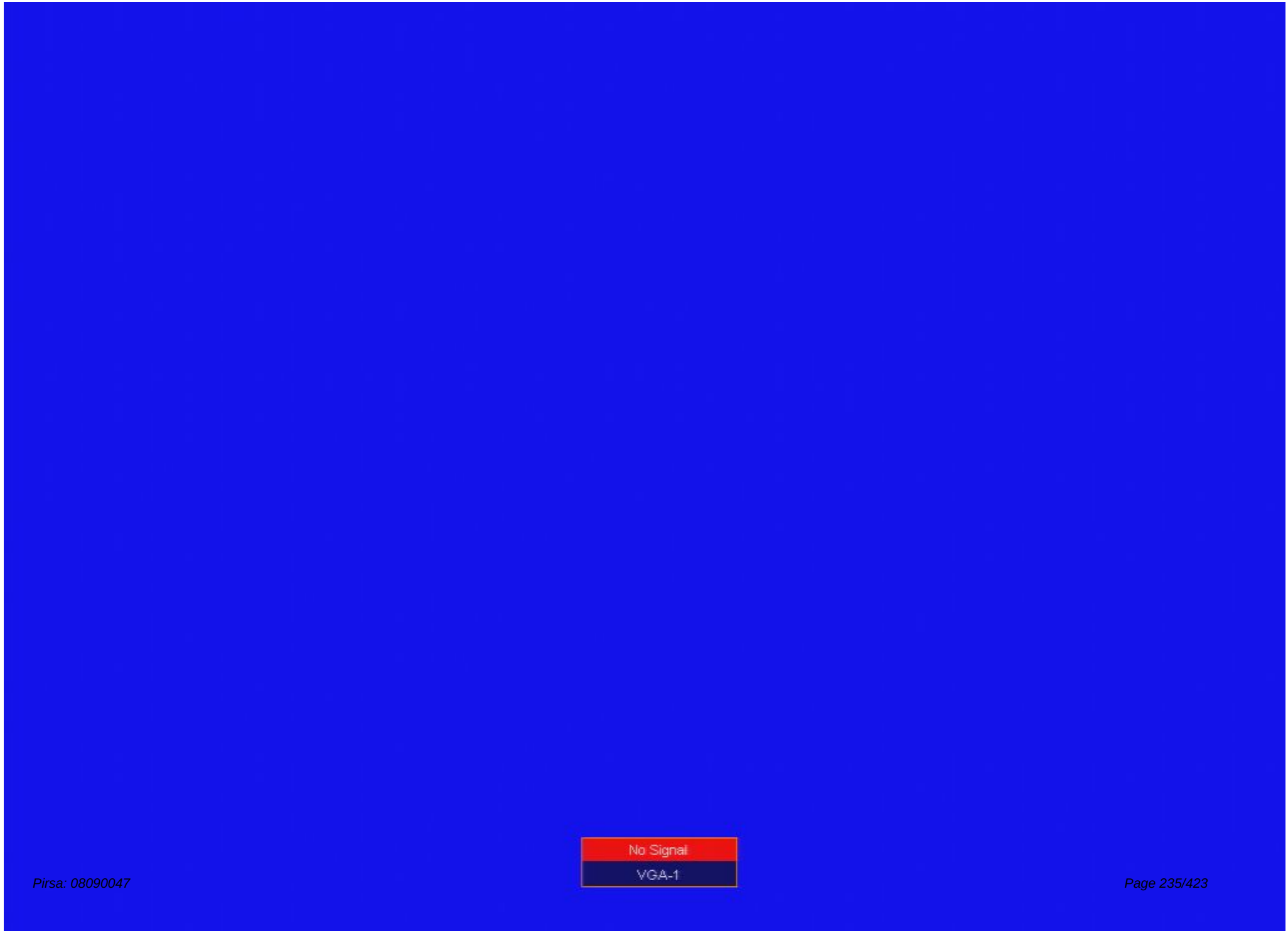

No Signal
VGA-1

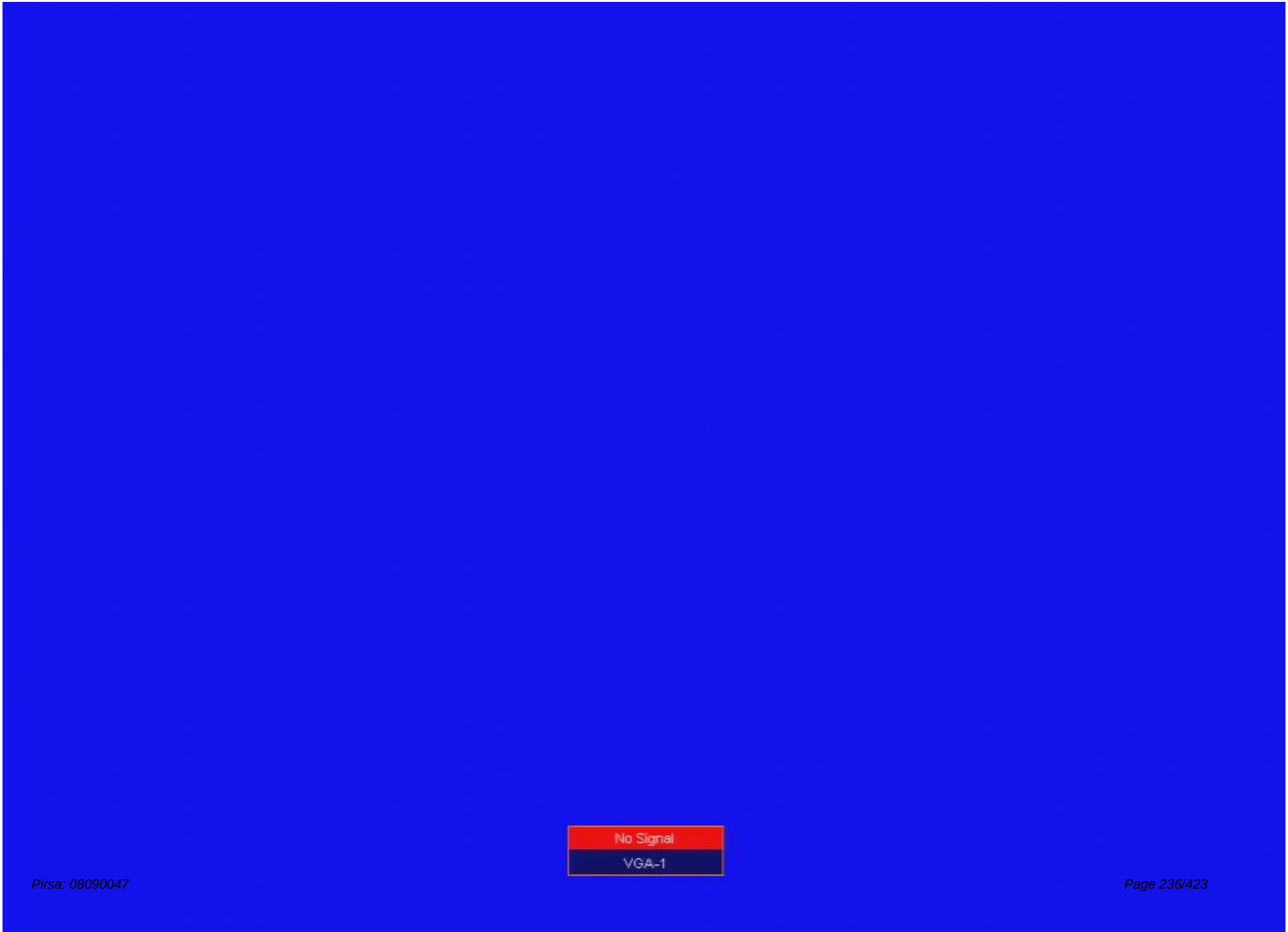

No Signal

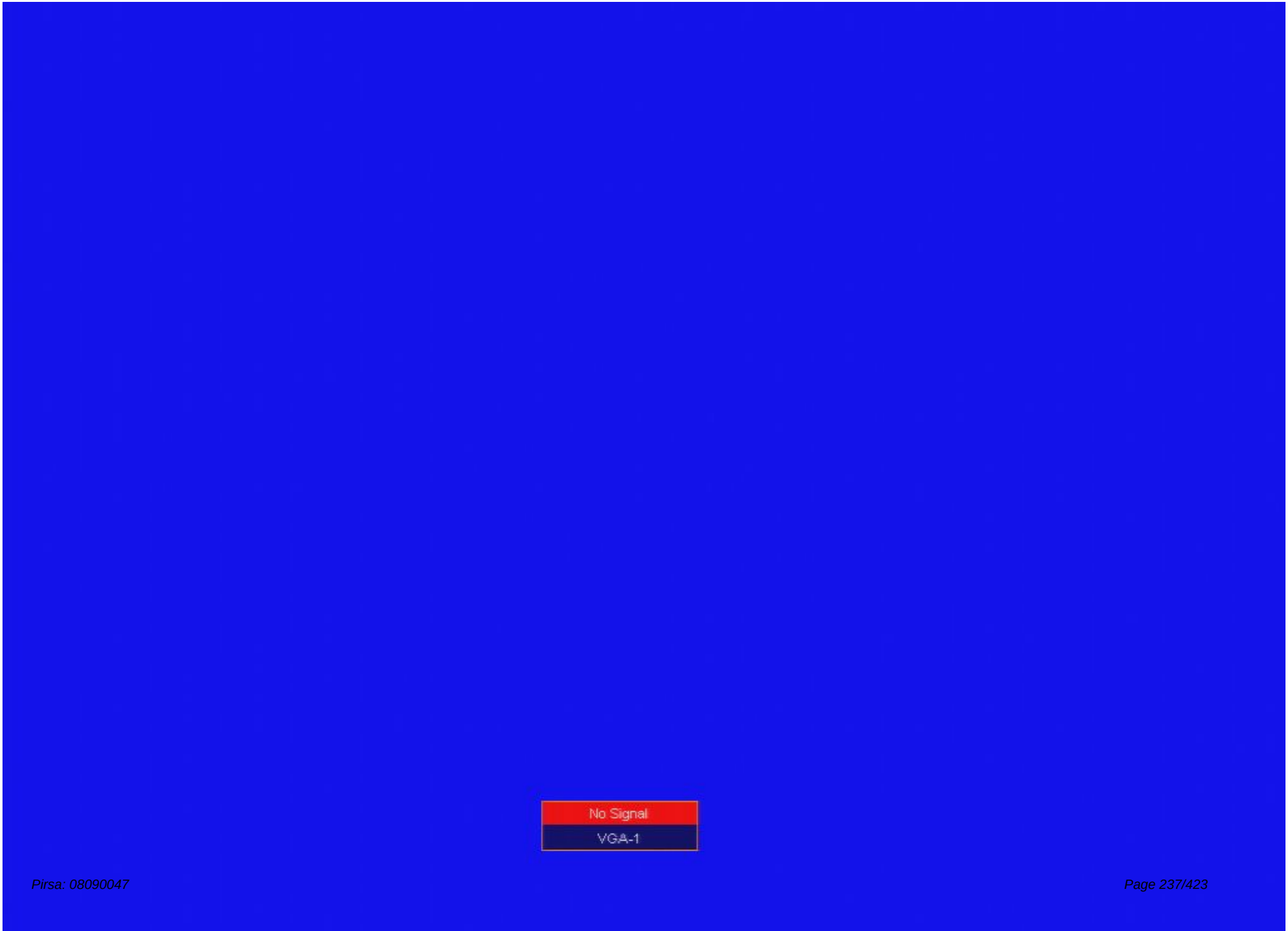

No Signal
VGA-1

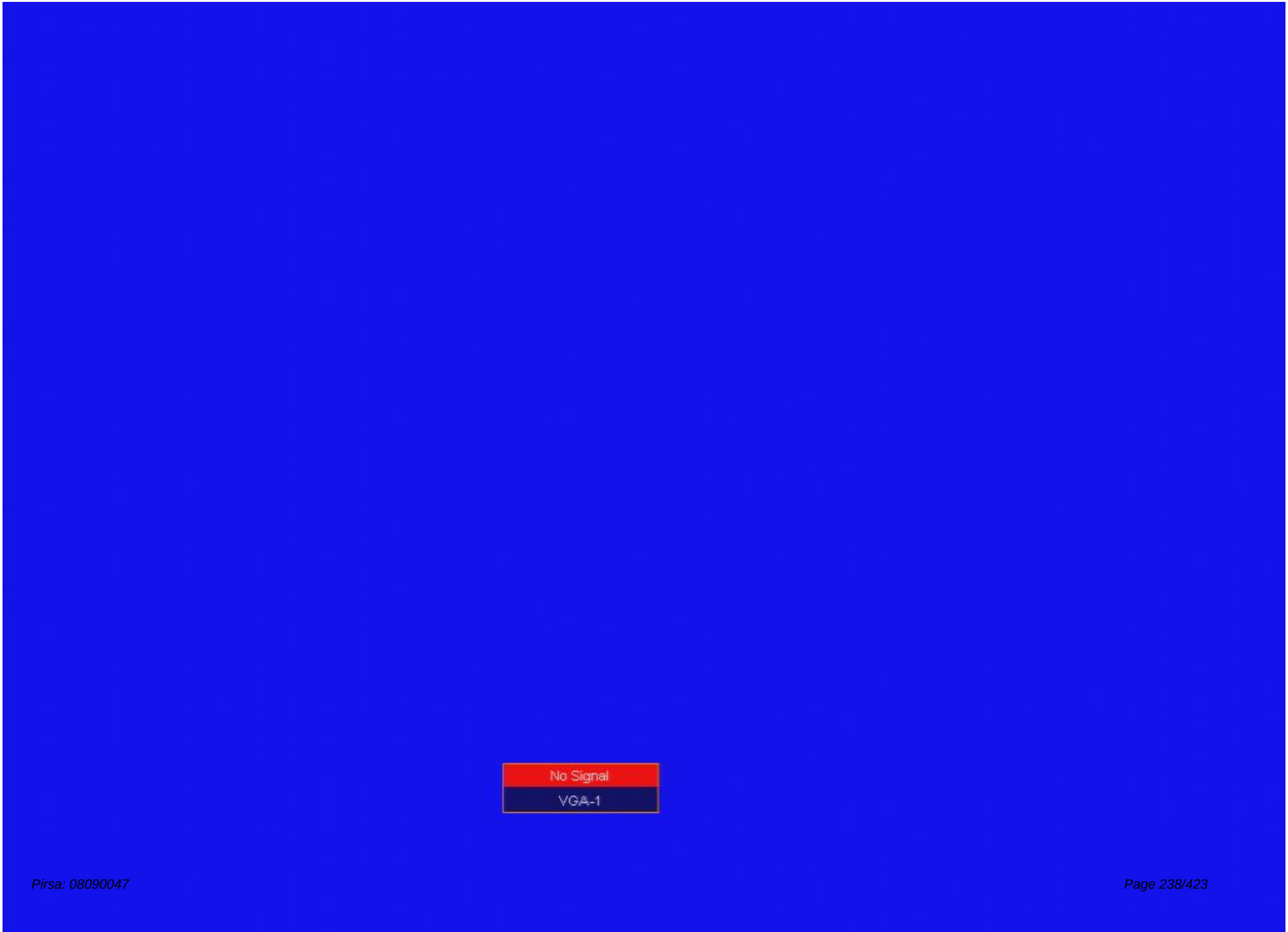

No Signal
VGA-1

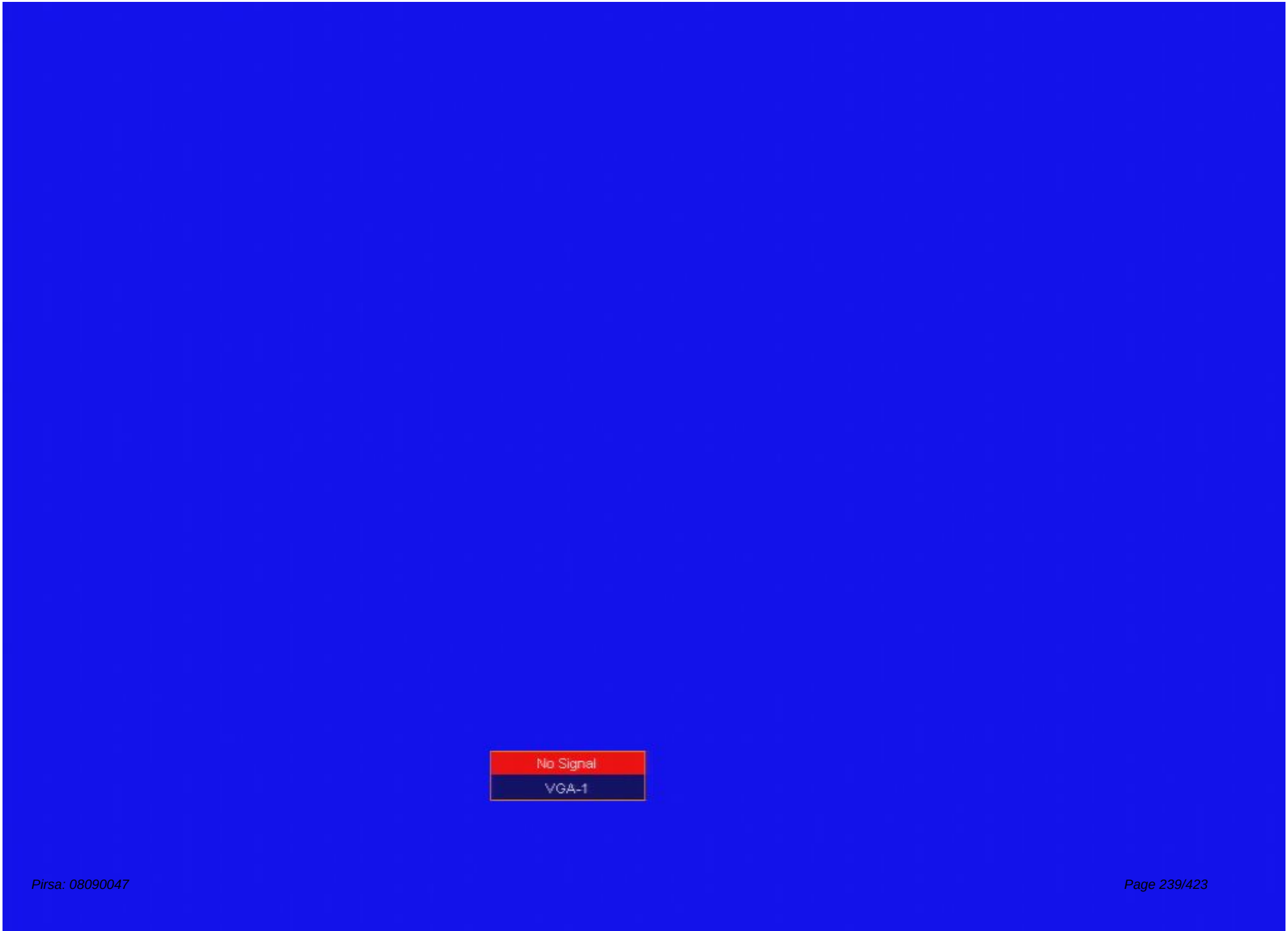

No Signal
VGA-1


No Signal
VGA-1

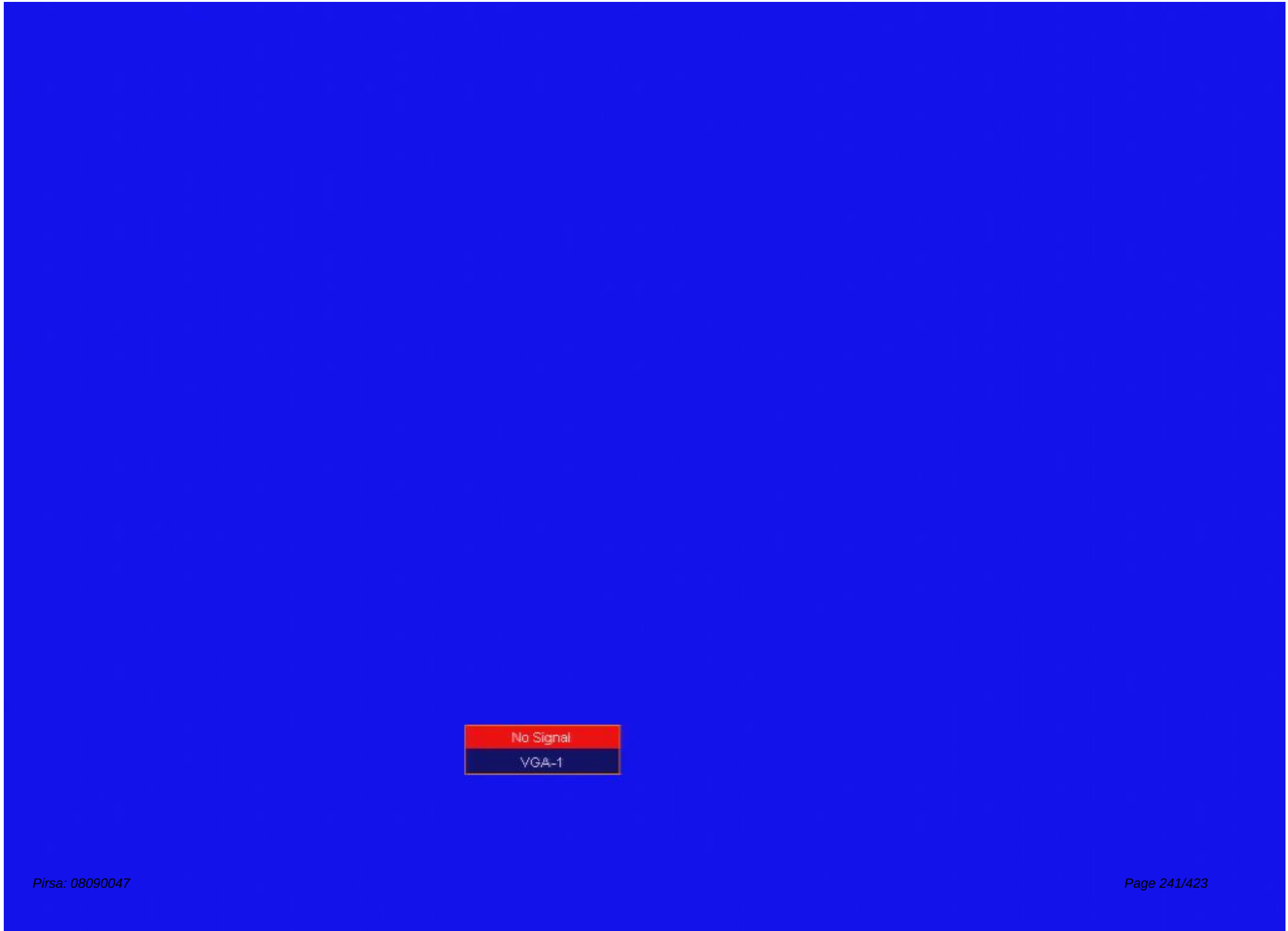

No Signal
VGA-1

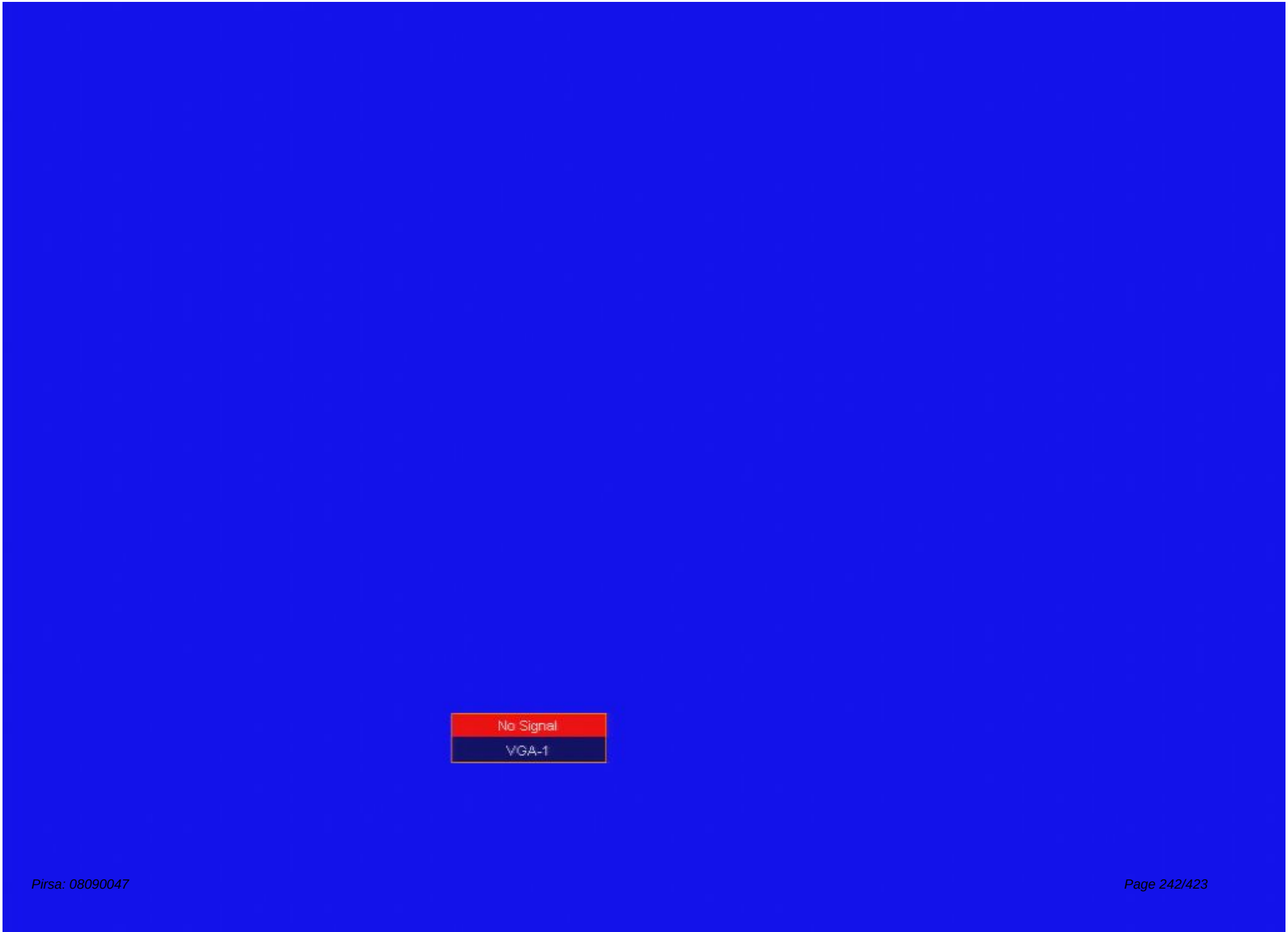

No Signal
VGA-1

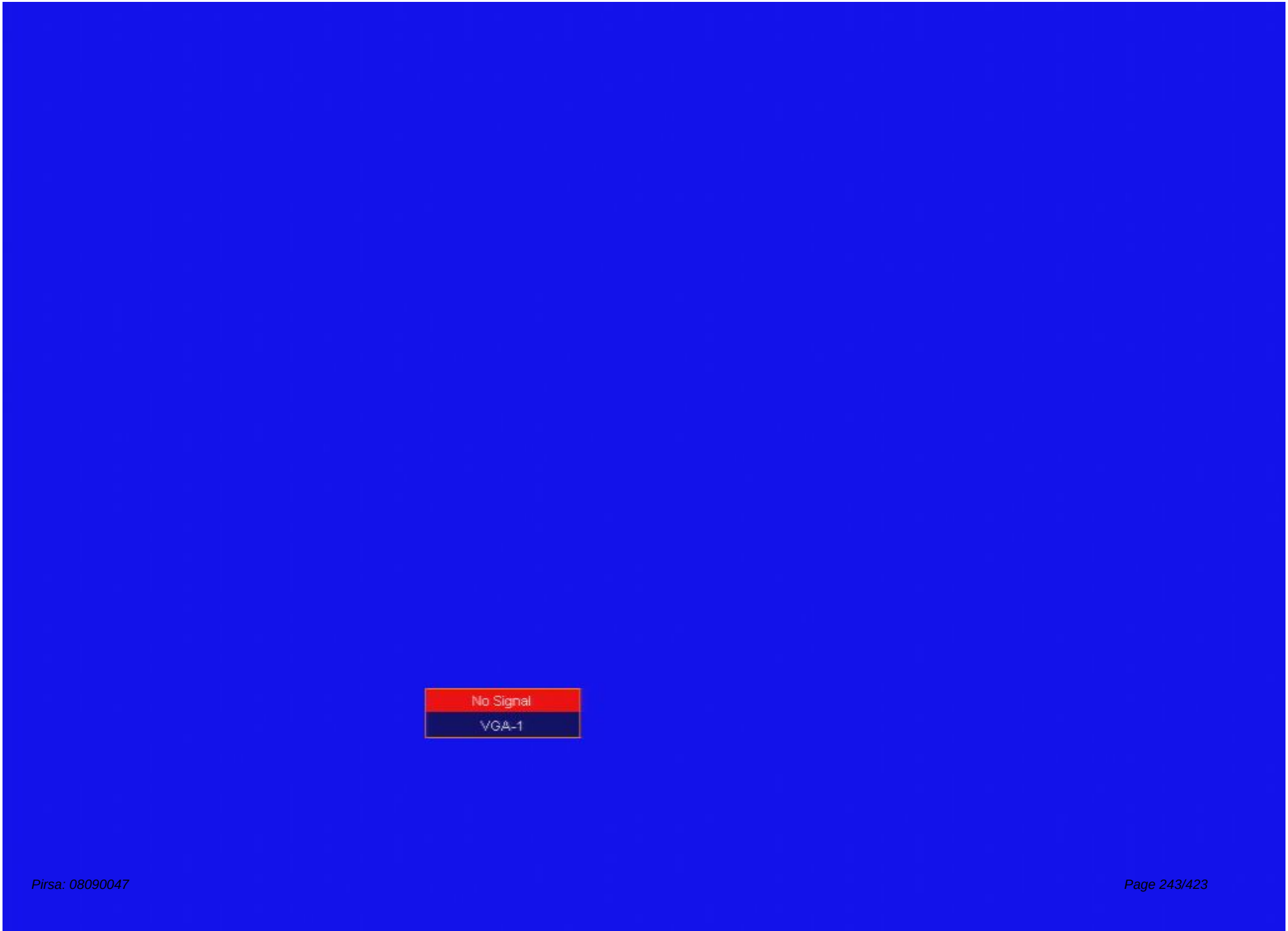

No Signal
VGA-1

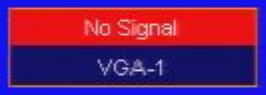

No Signal
VGA-1

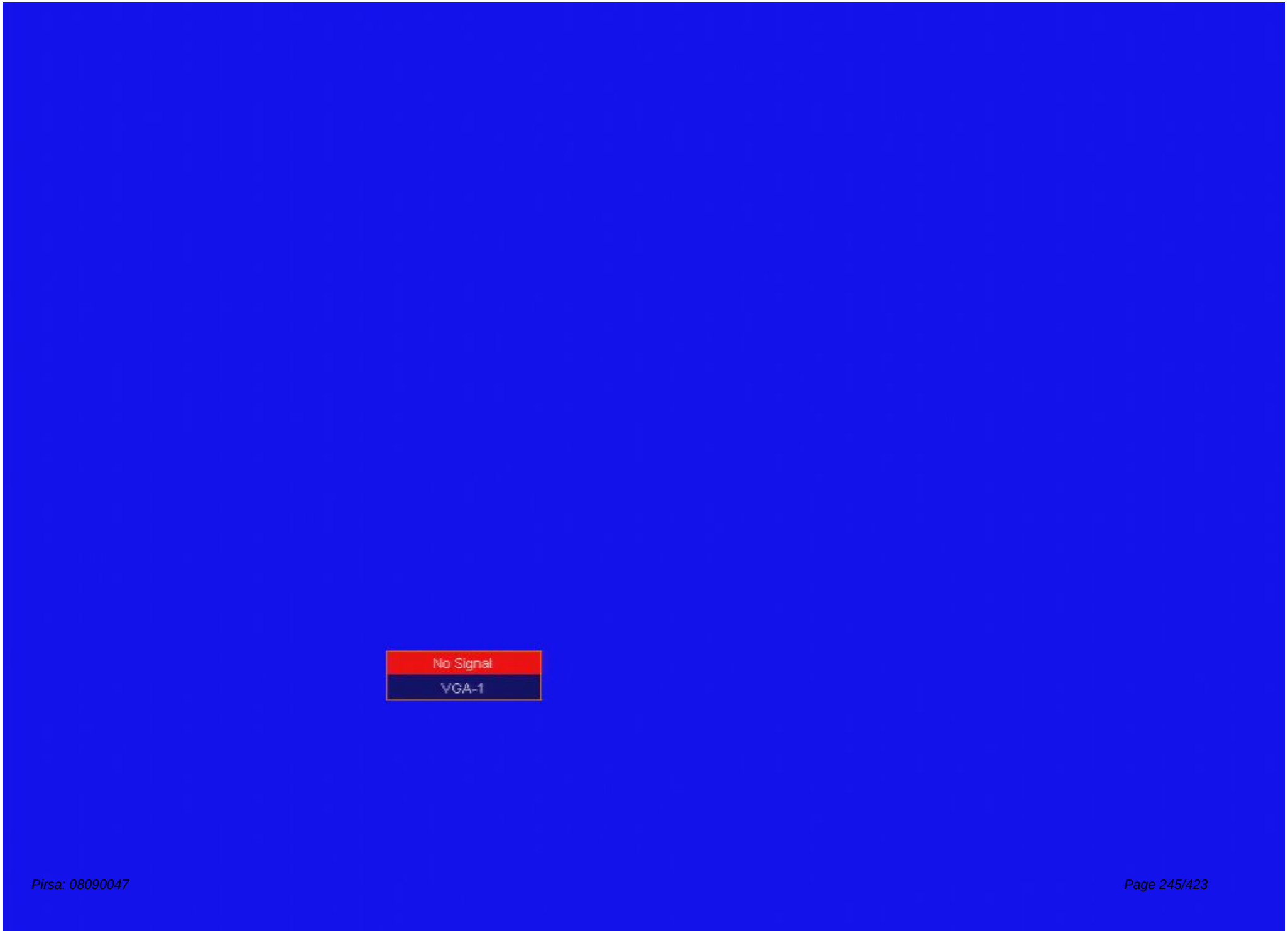

No Signal
VGA-1

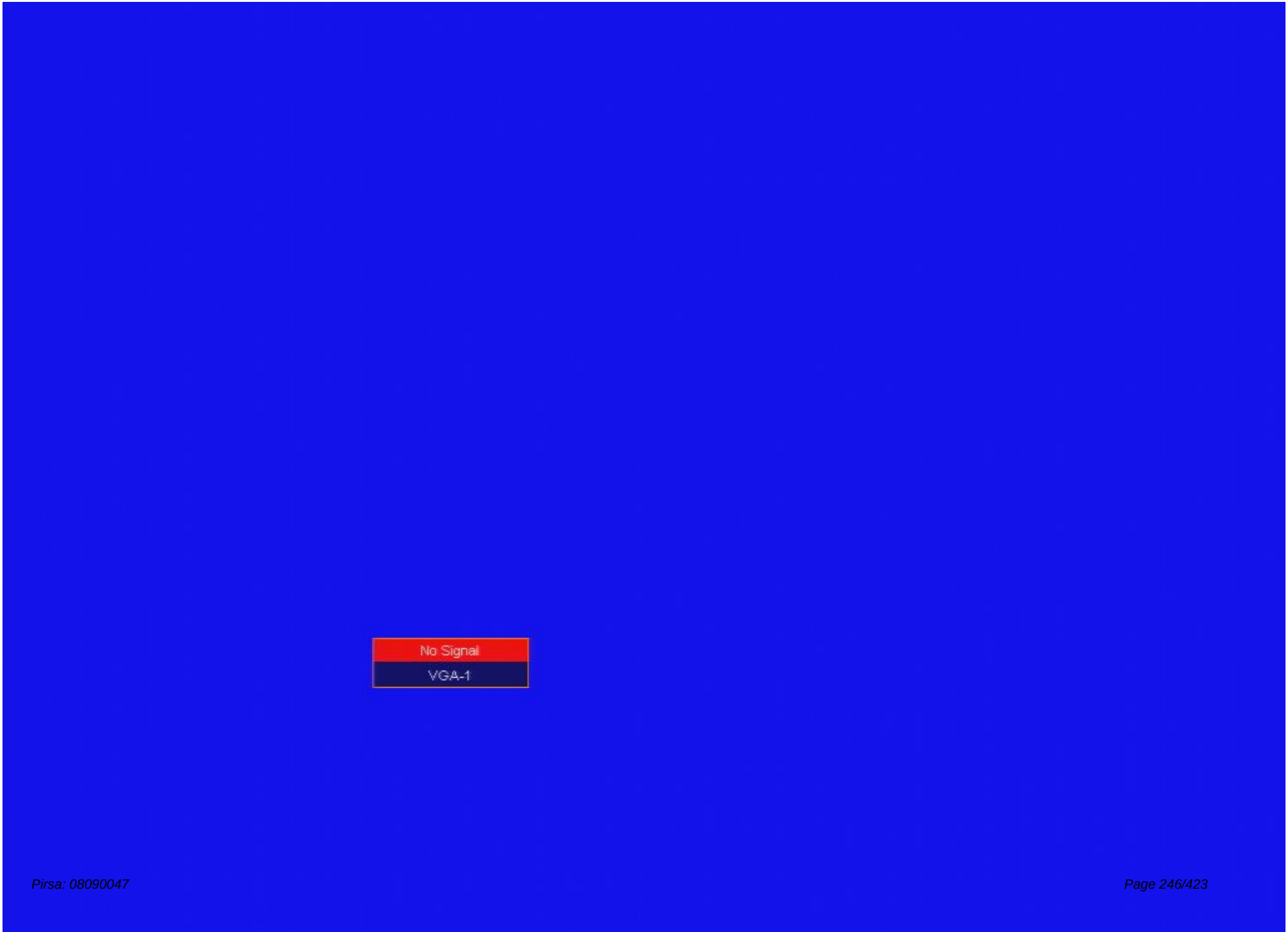

No Signal
VGA-1

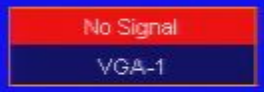

No Signal
VGA-1


No Signal
VGA-1

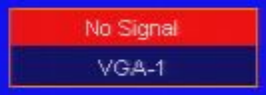

No Signal
VGA-1

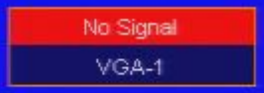

No Signal
VGA-1

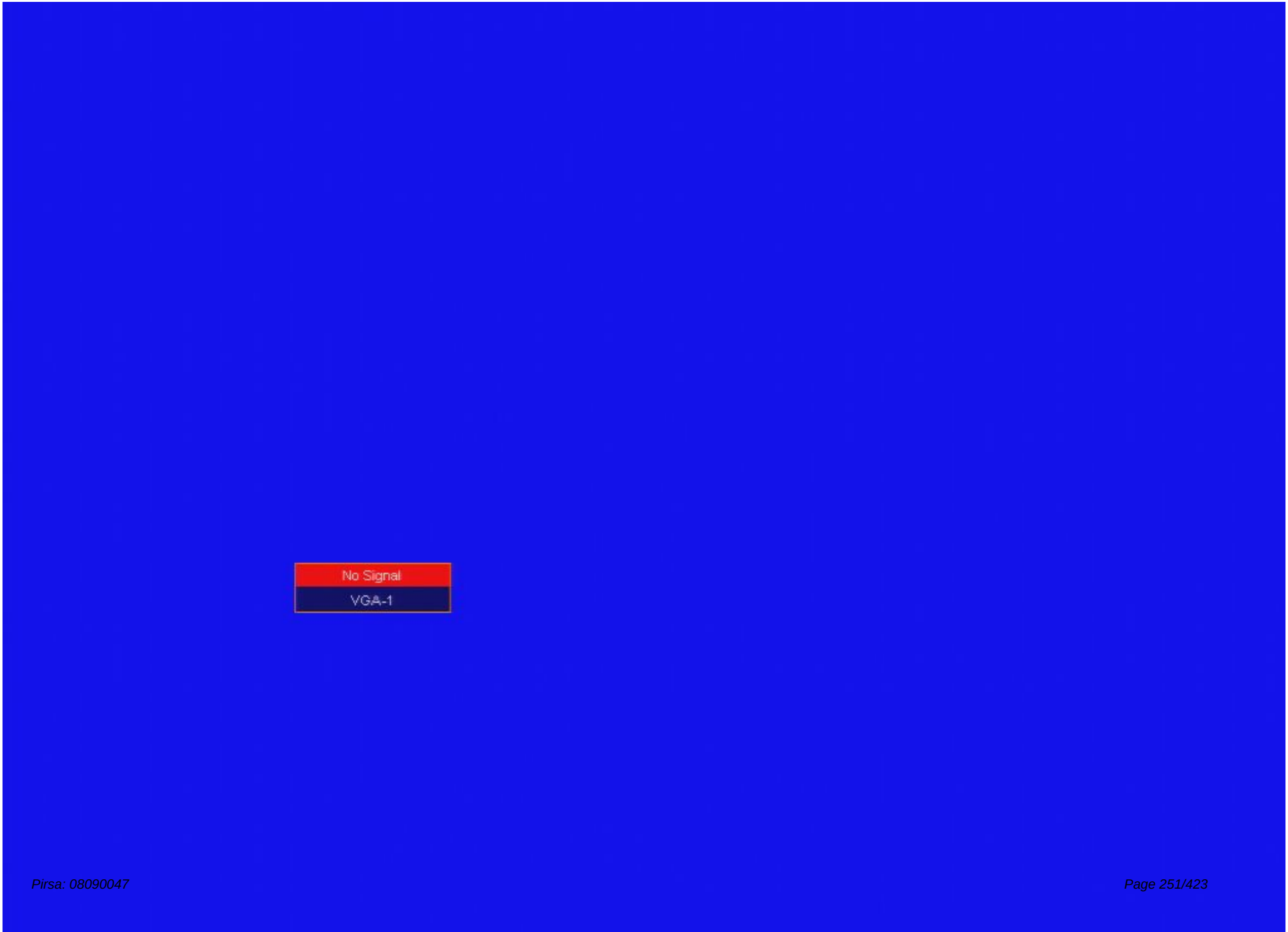

No Signal
VGA-1

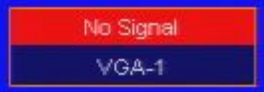

No Signal
VGA-1


No Signal
VGA-1

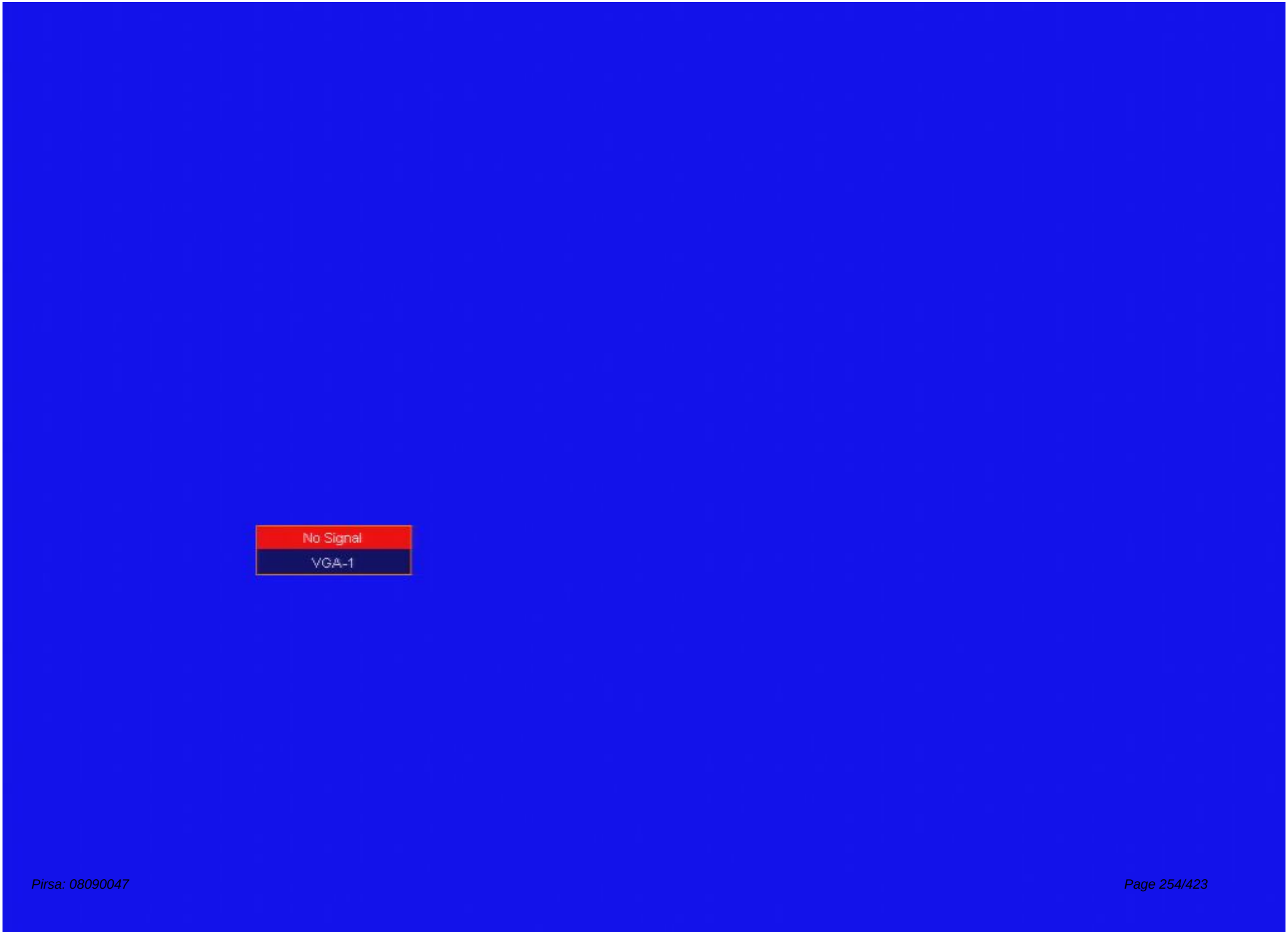

No Signal
VGA-1

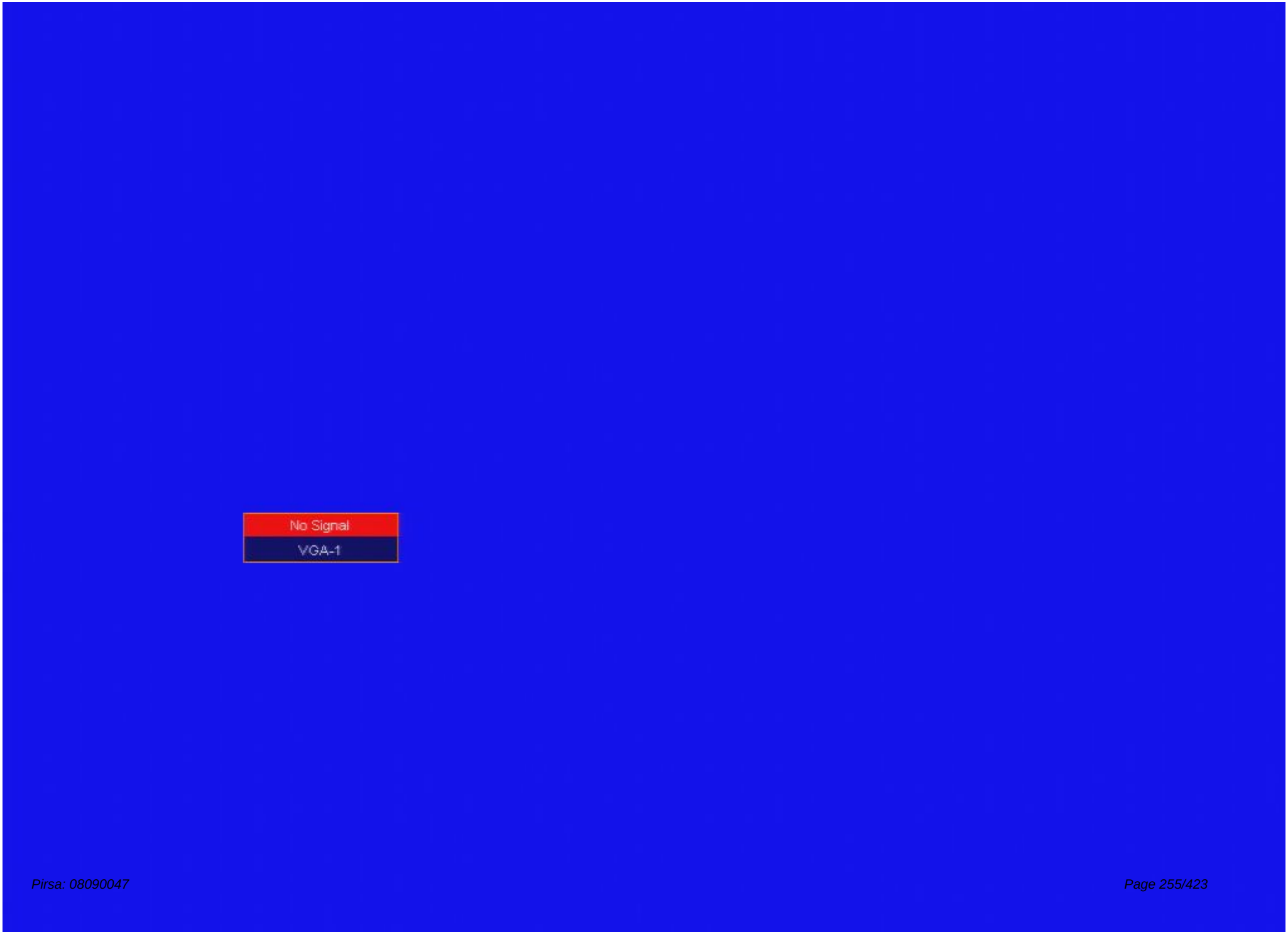

No Signal
VGA-1


No Signal
VGA-1

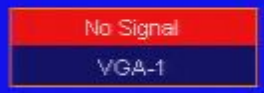

No Signal
VGA-1

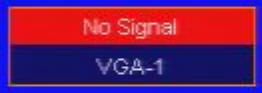

No Signal
VGA-1


No Signal
VGA-1

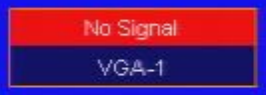

No Signal
VGA-1

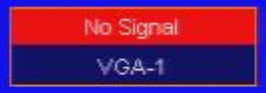

No Signal
VGA-1

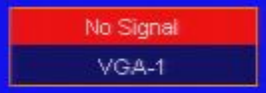

No Signal
VGA-1


No Signal
VGA-1

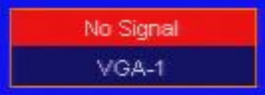

No Signal
VGA-1


No Signal
VGA-1

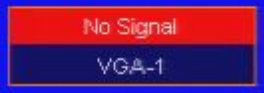

No Signal
VGA-1

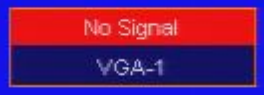

No Signal
VGA-1

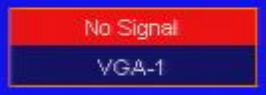

No Signal
VGA-1

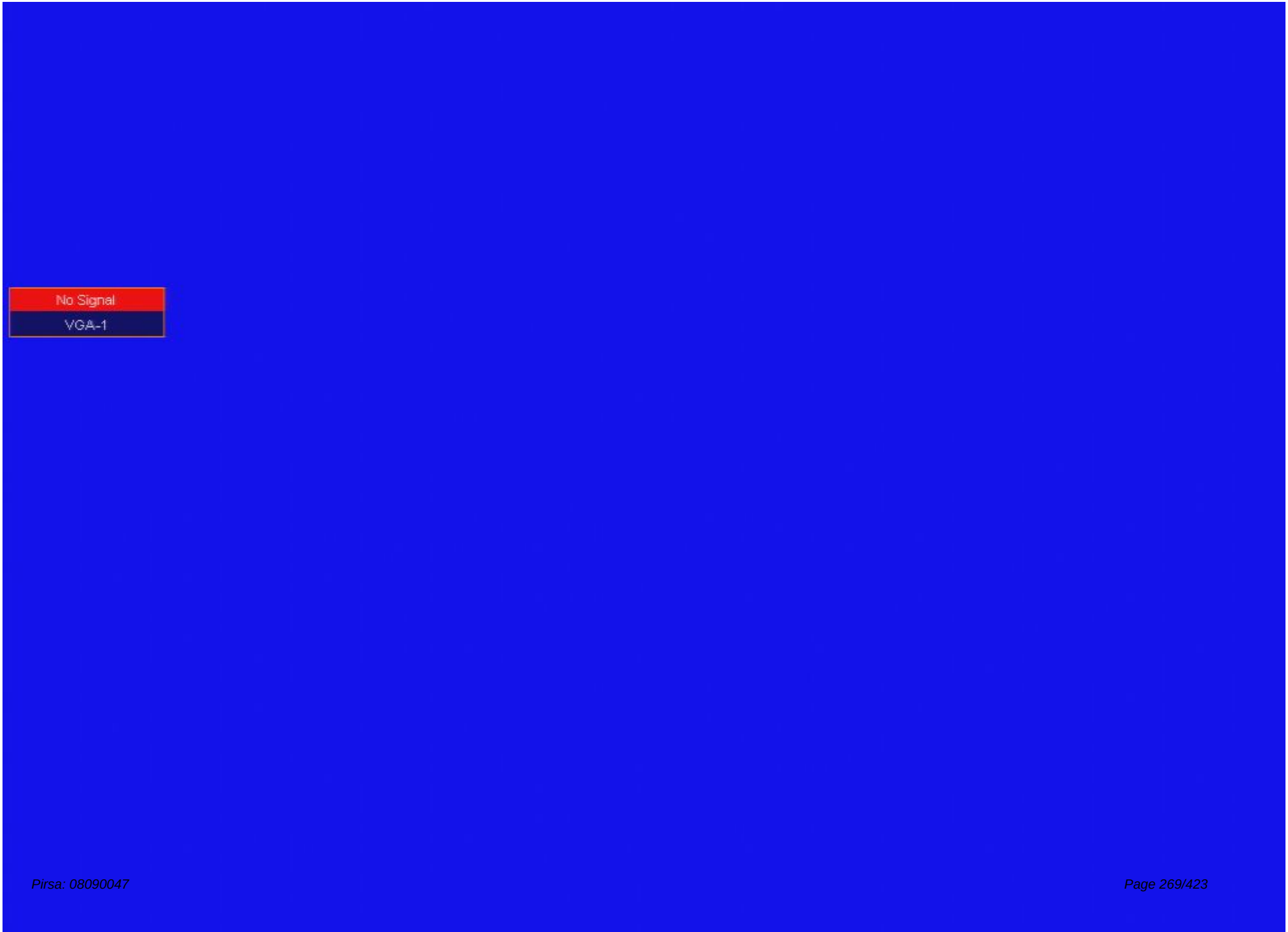

No Signal
VGA-1

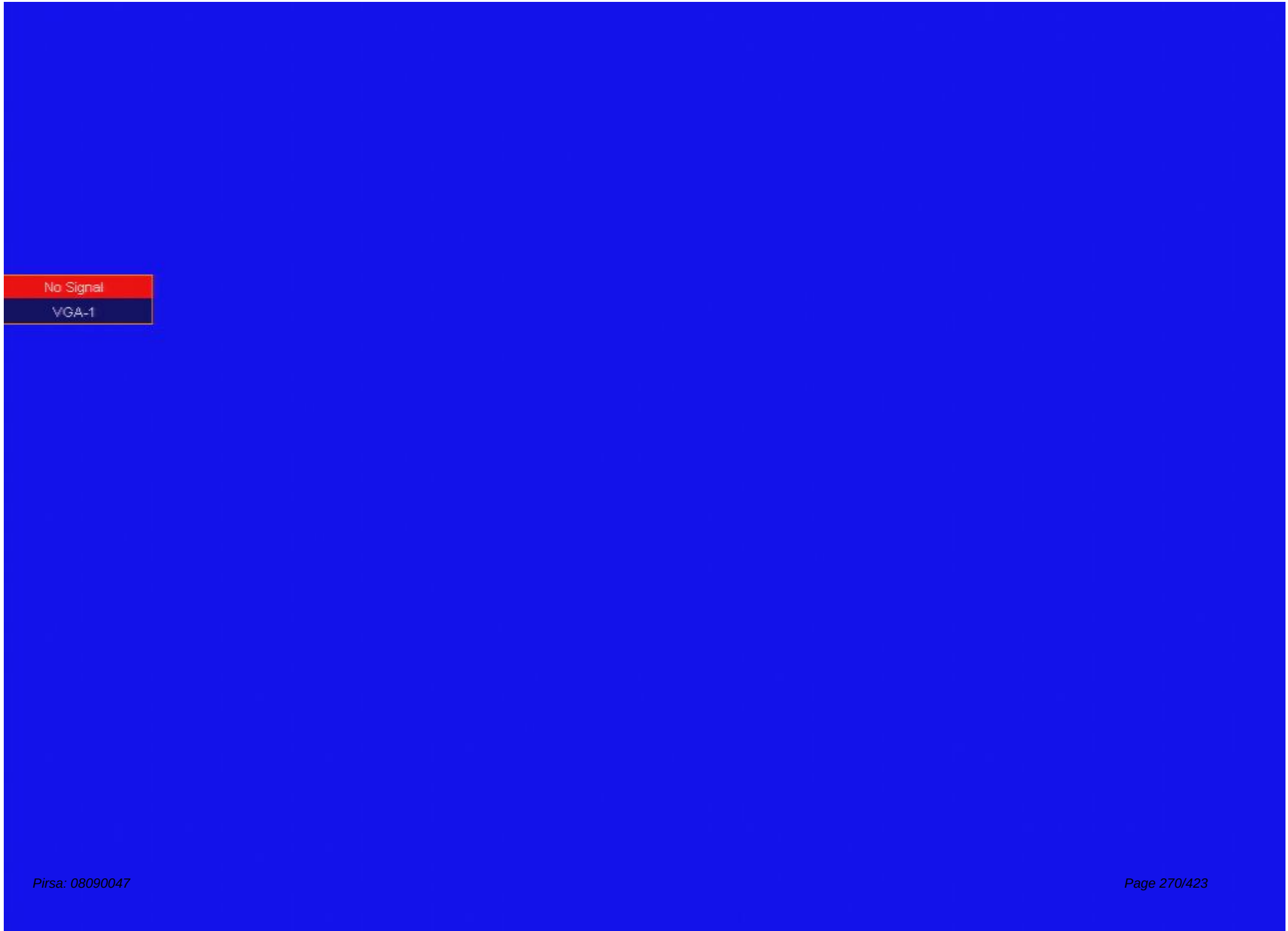

No Signal
VGA-1

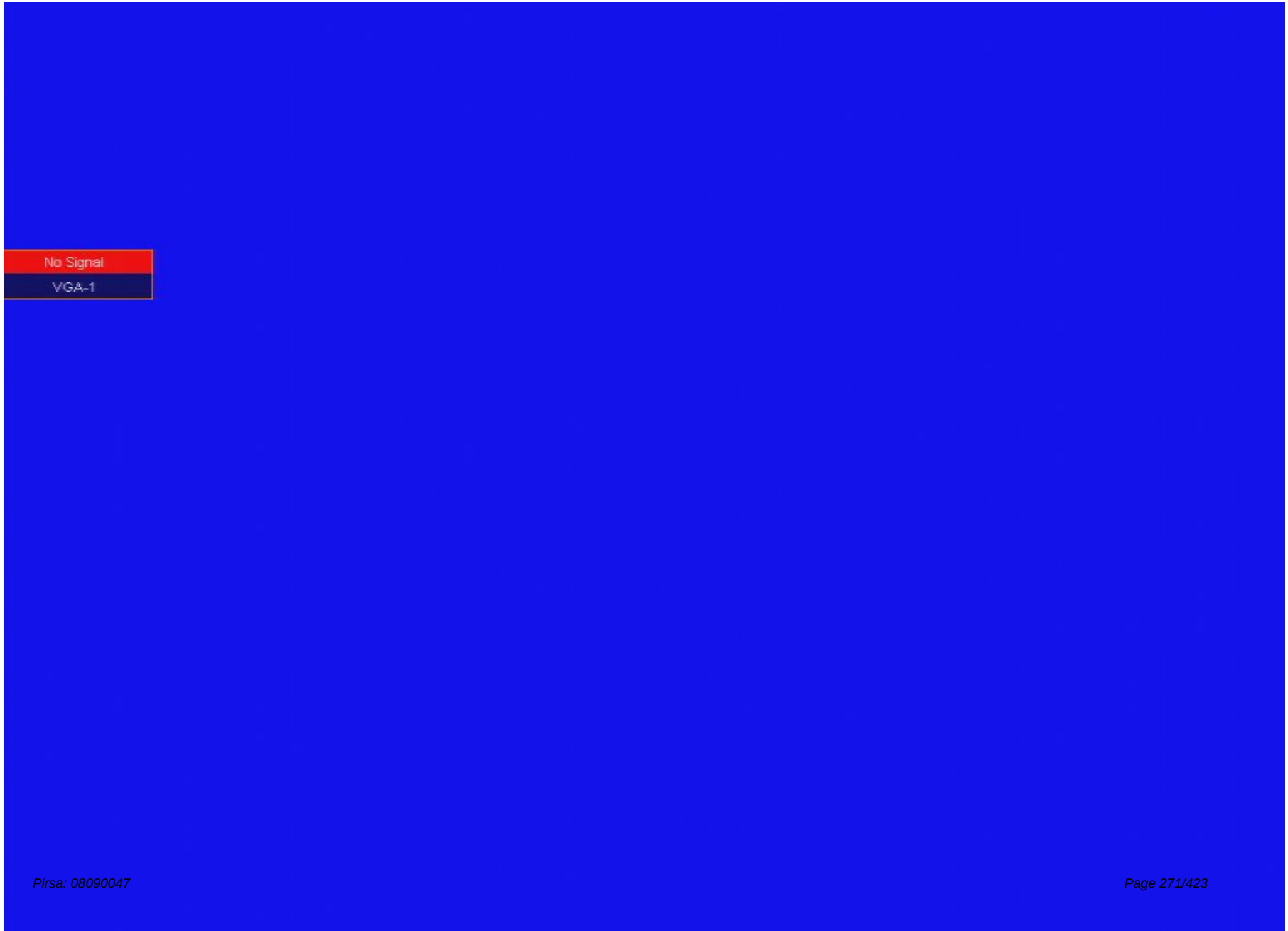

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

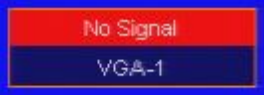

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

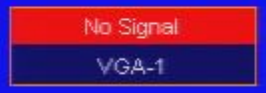

No Signal
VGA-1

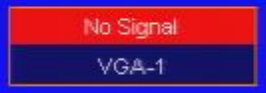

No Signal
VGA-1

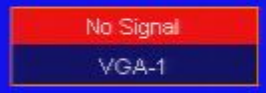

No Signal
VGA-1

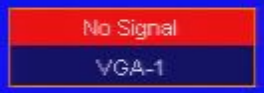

No Signal
VGA-1

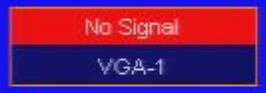

No Signal
VGA-1

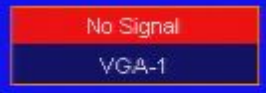

No Signal
VGA-1

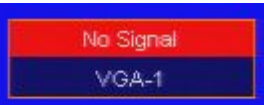

No Signal
VGA-1

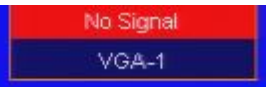

No Signal
VGA-1

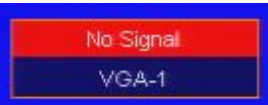

No Signal
VGA-1

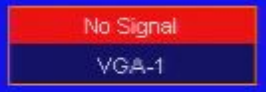

No Signal
VGA-1

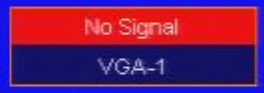

No Signal
VGA-1

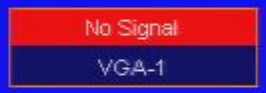

No Signal
VGA-1

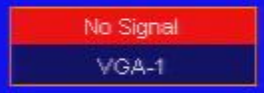

No Signal
VGA-1

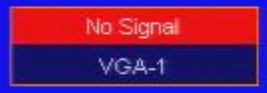

No Signal
VGA-1

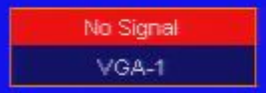

No Signal
VGA-1

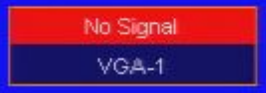

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

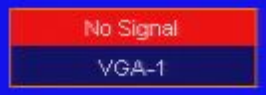

No Signal
VGA-1


No Signal
VGA-1

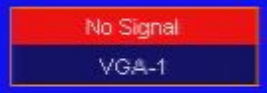

No Signal
VGA-1

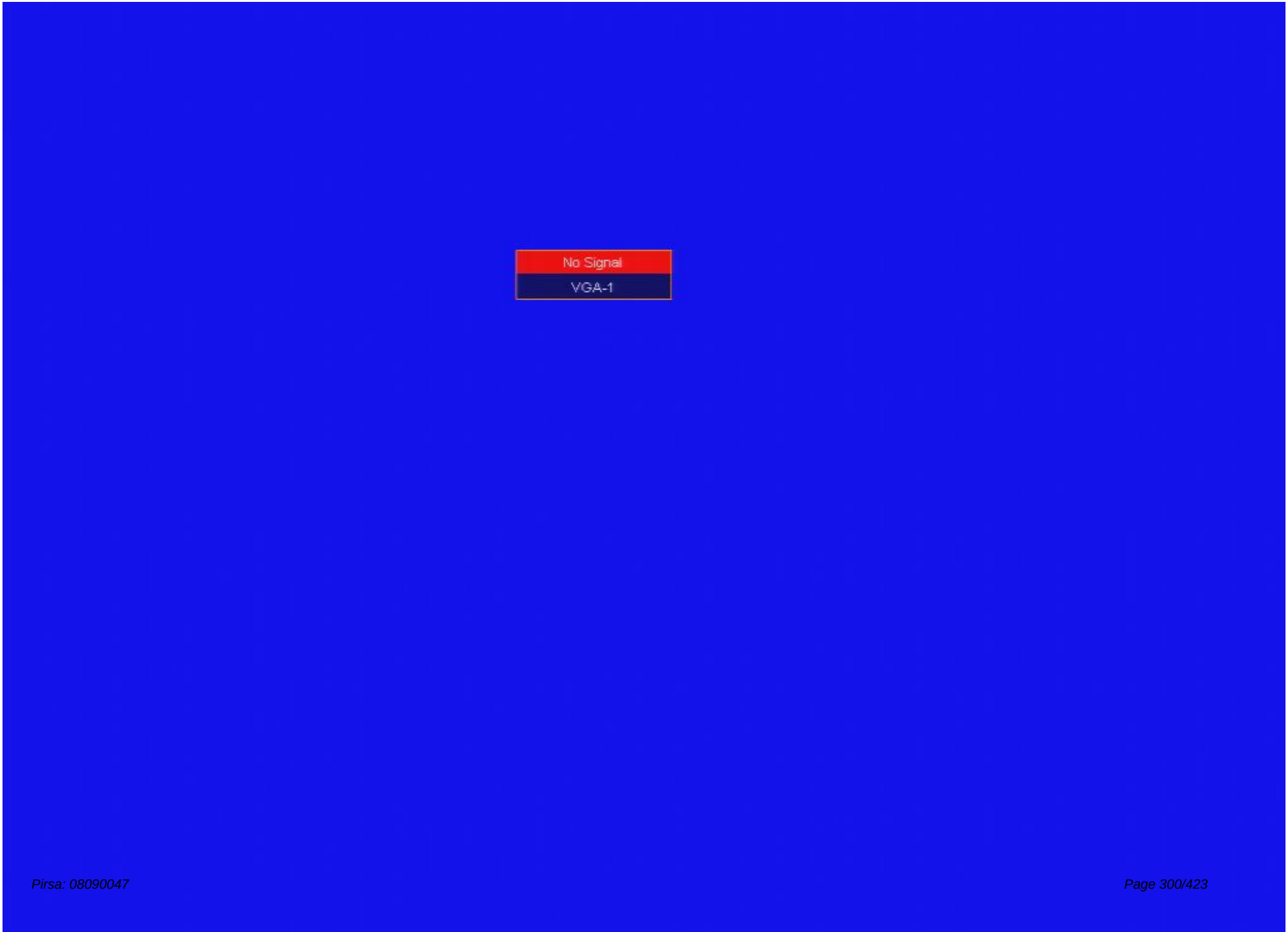

No Signal
VGA-1

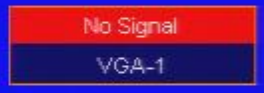

No Signal
VGA-1

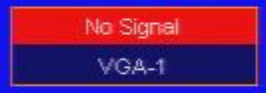

No Signal
VGA-1


No Signal
VGA-1

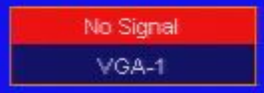

No Signal
VGA-1

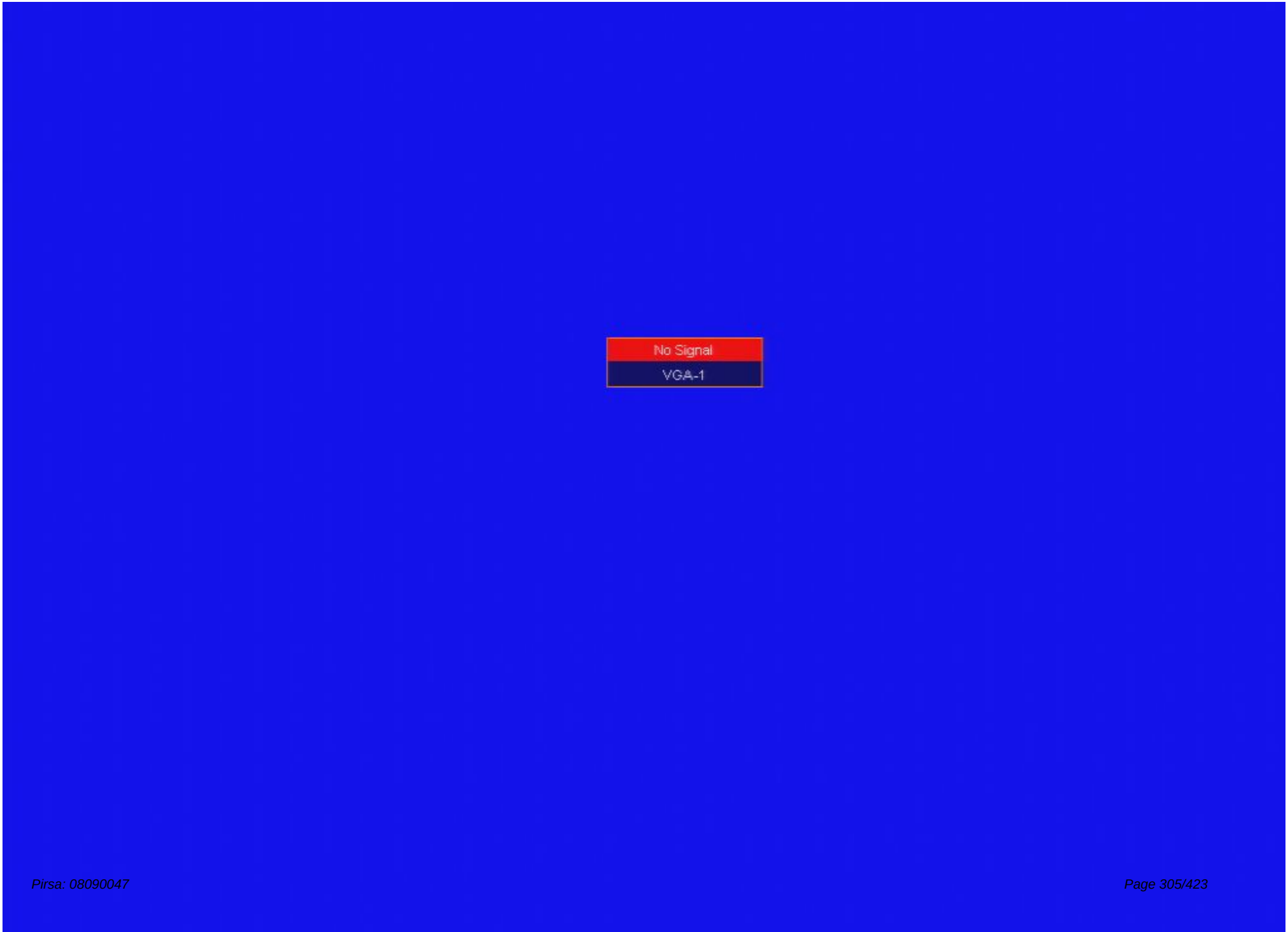

No Signal
VGA-1

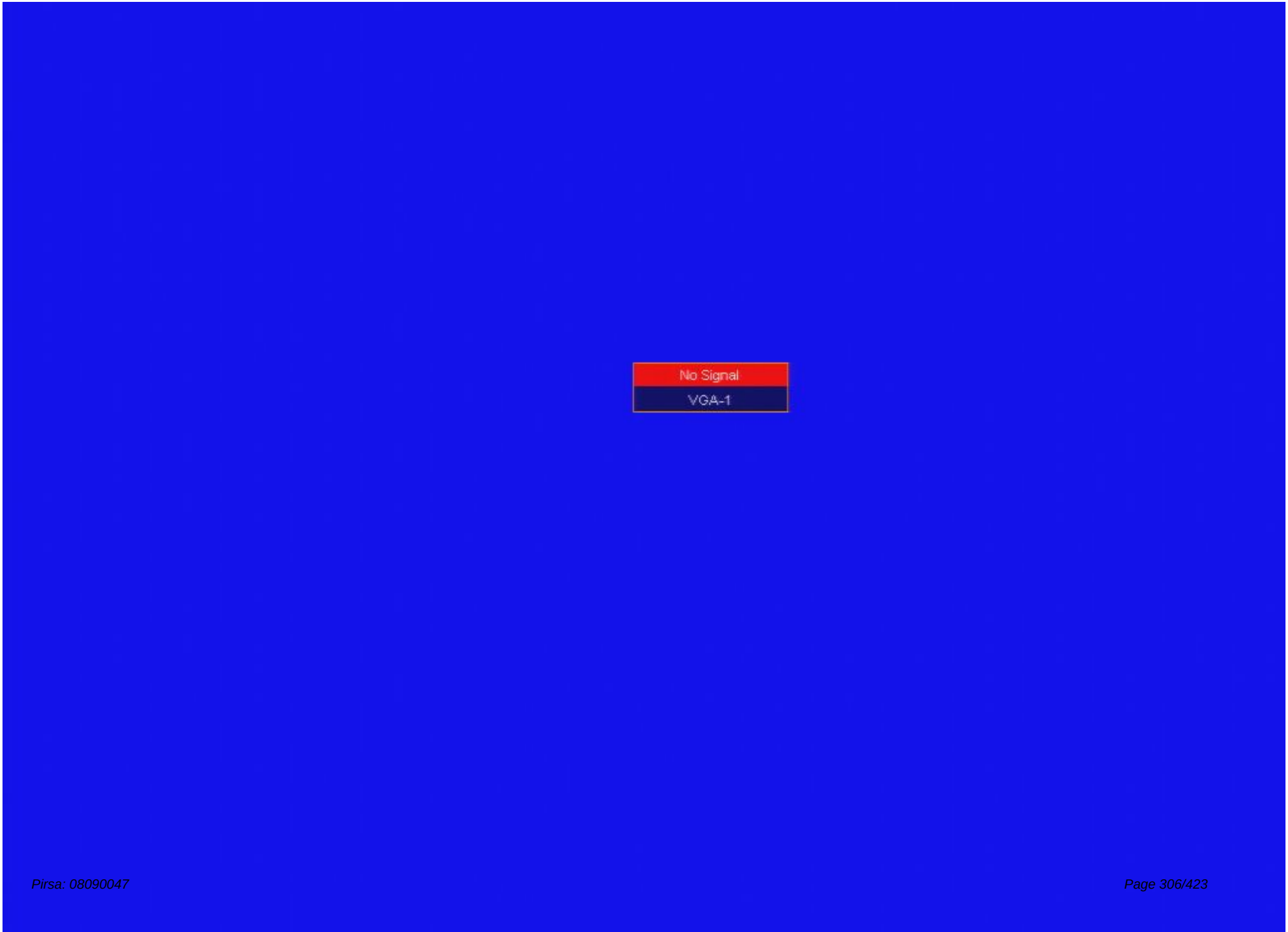

No Signal
VGA-1

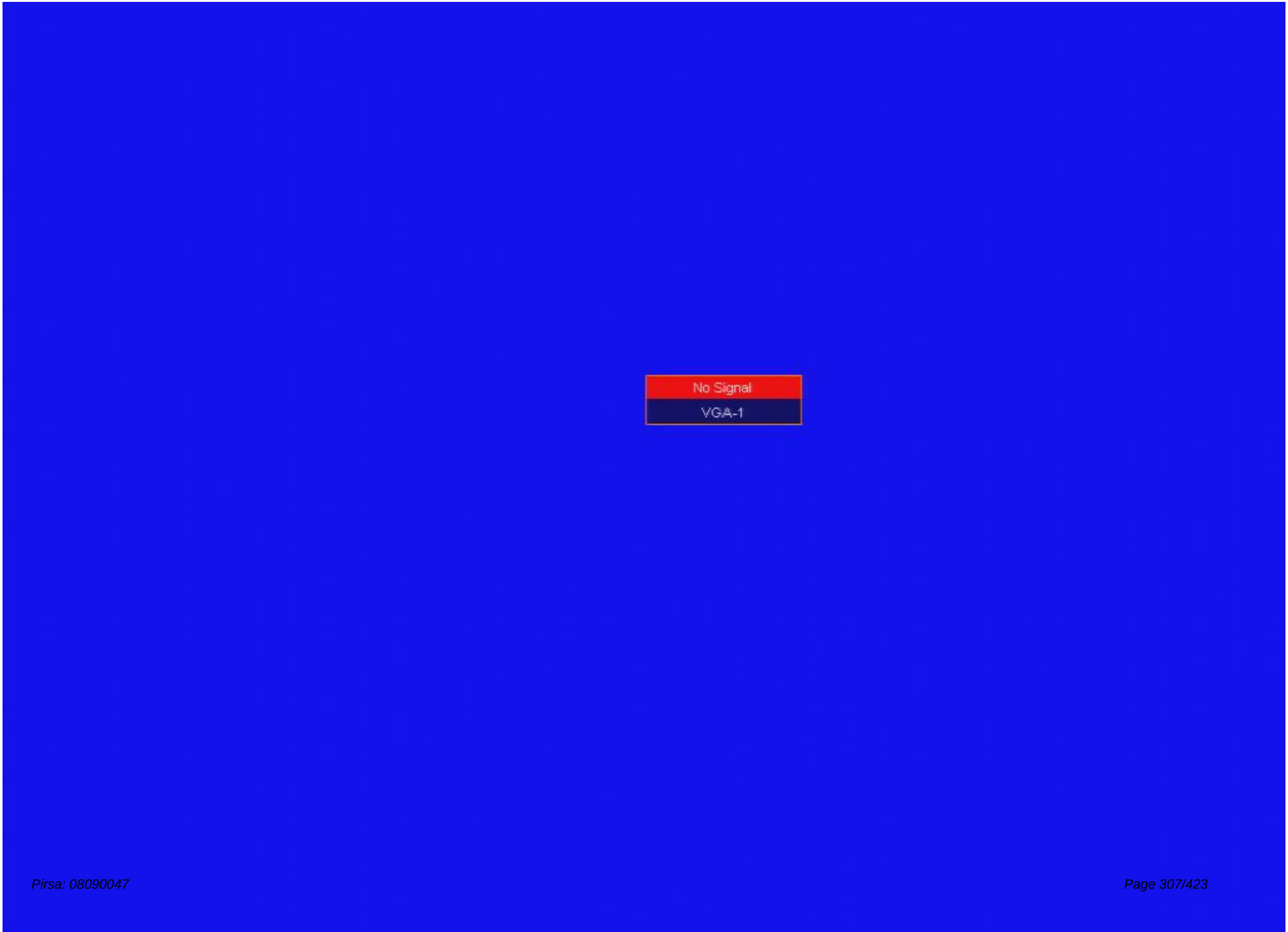

No Signal
VGA-1

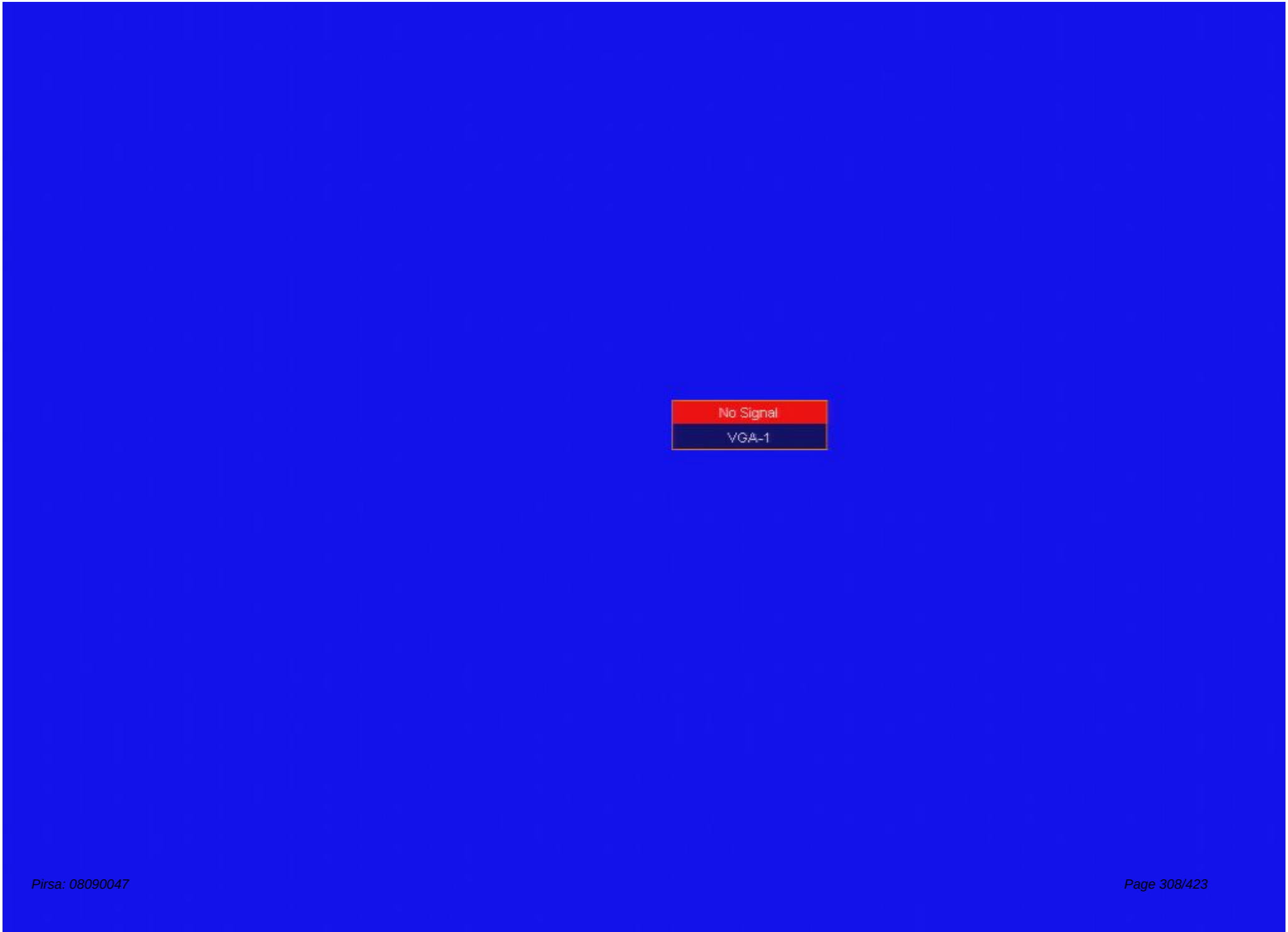

No Signal
VGA-1

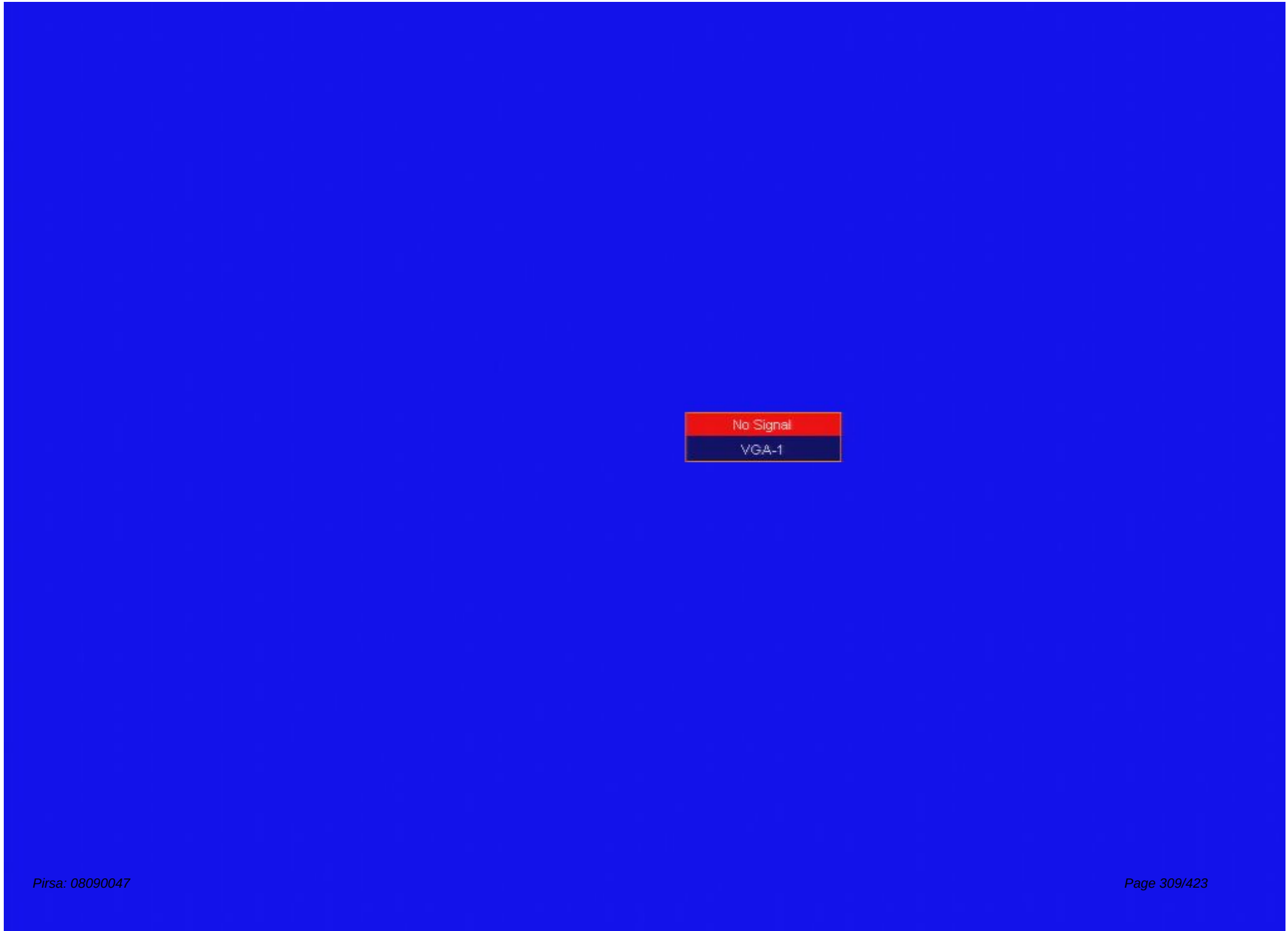

No Signal
VGA-1

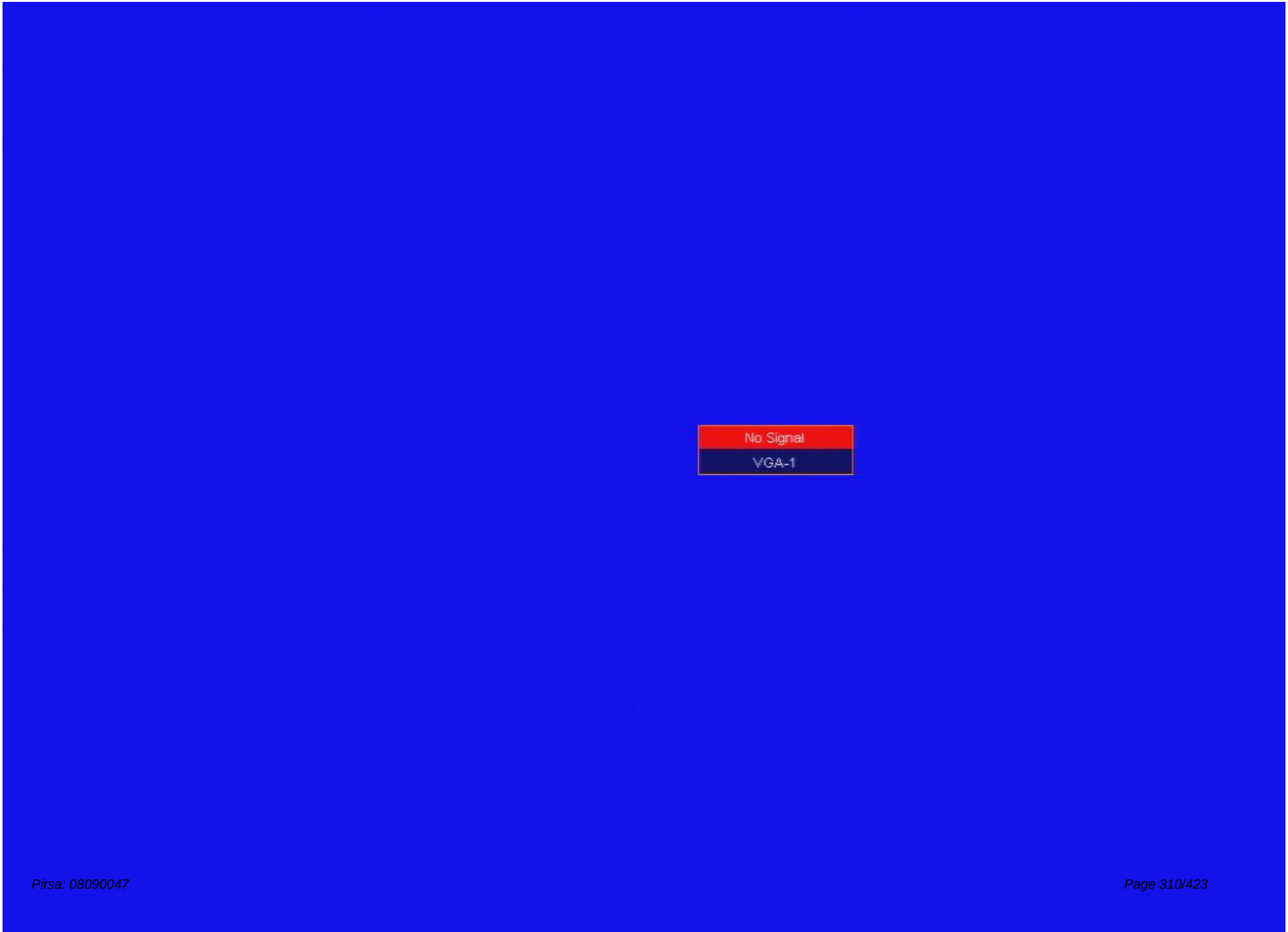

No Signal
VGA-1

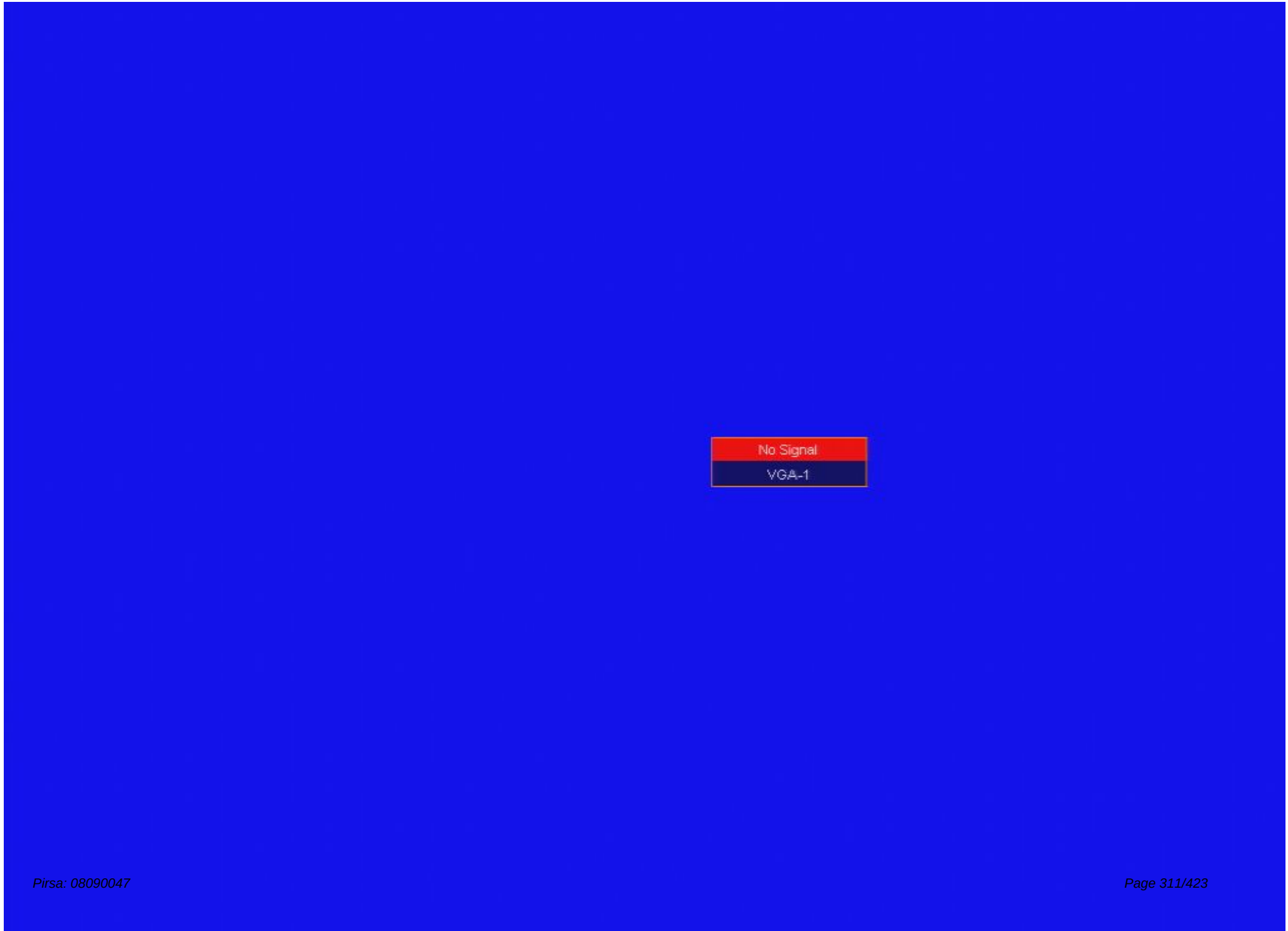

No Signal
VGA-1

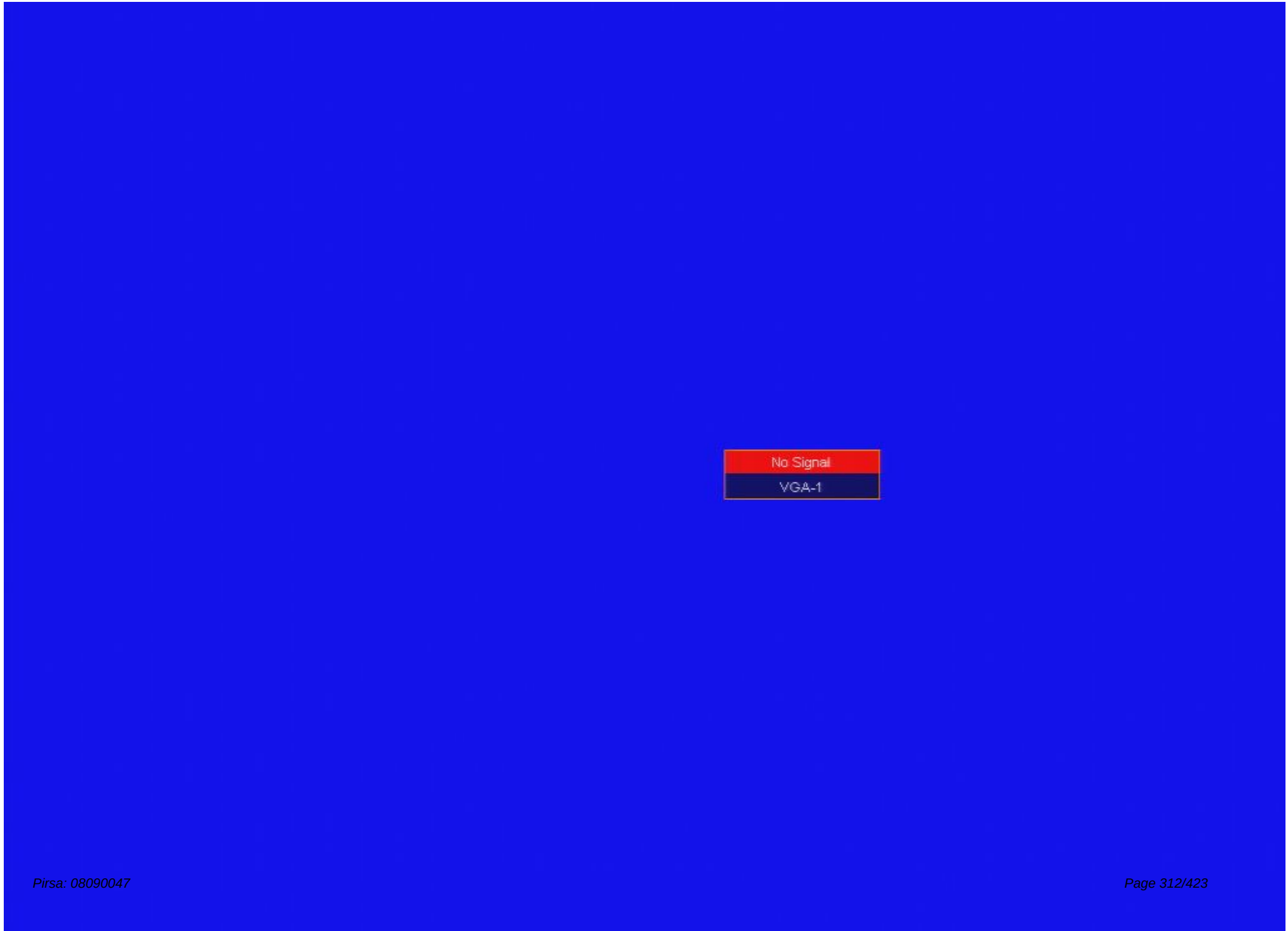

No Signal
VGA-1

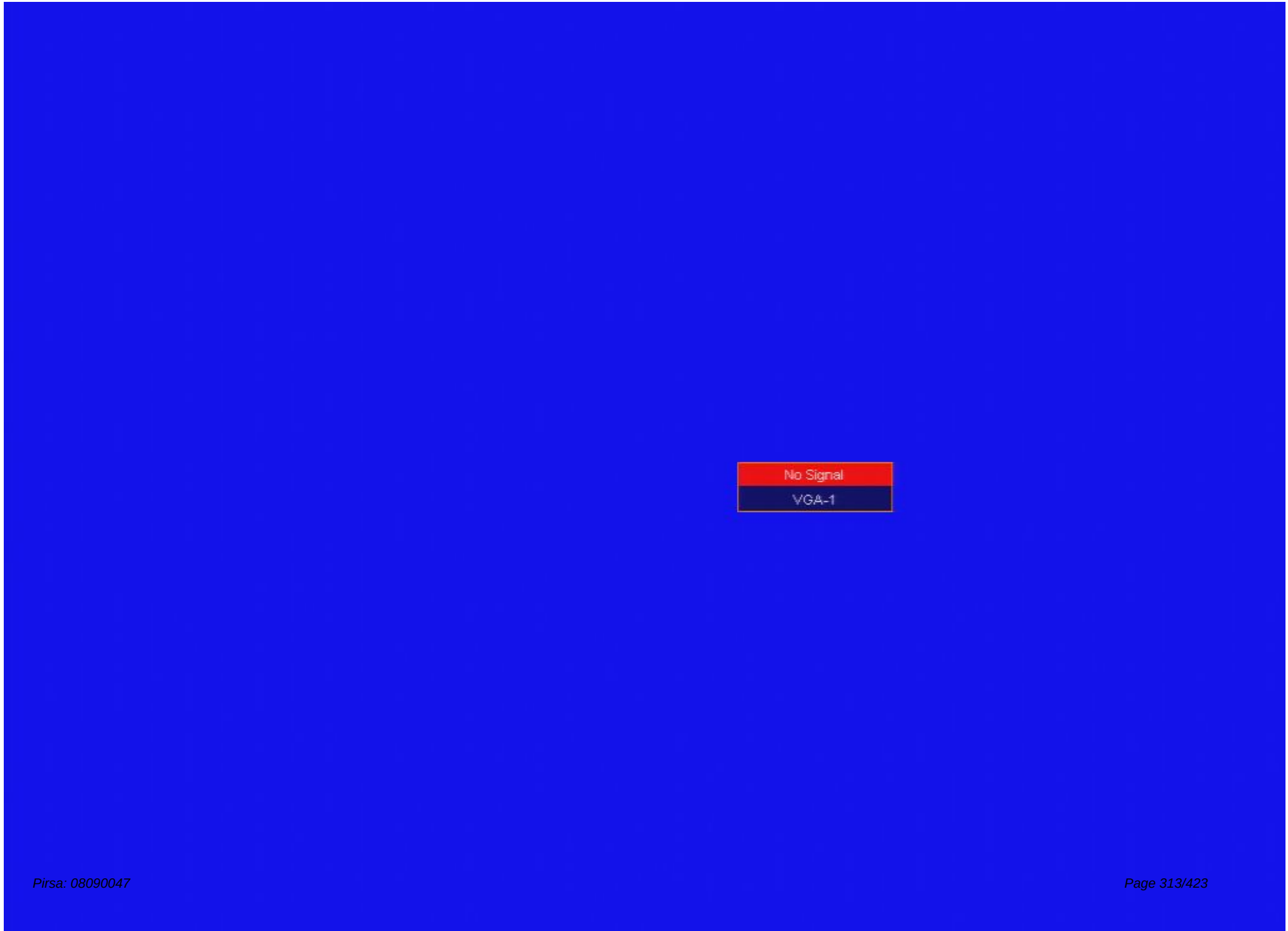

No Signal
VGA-1

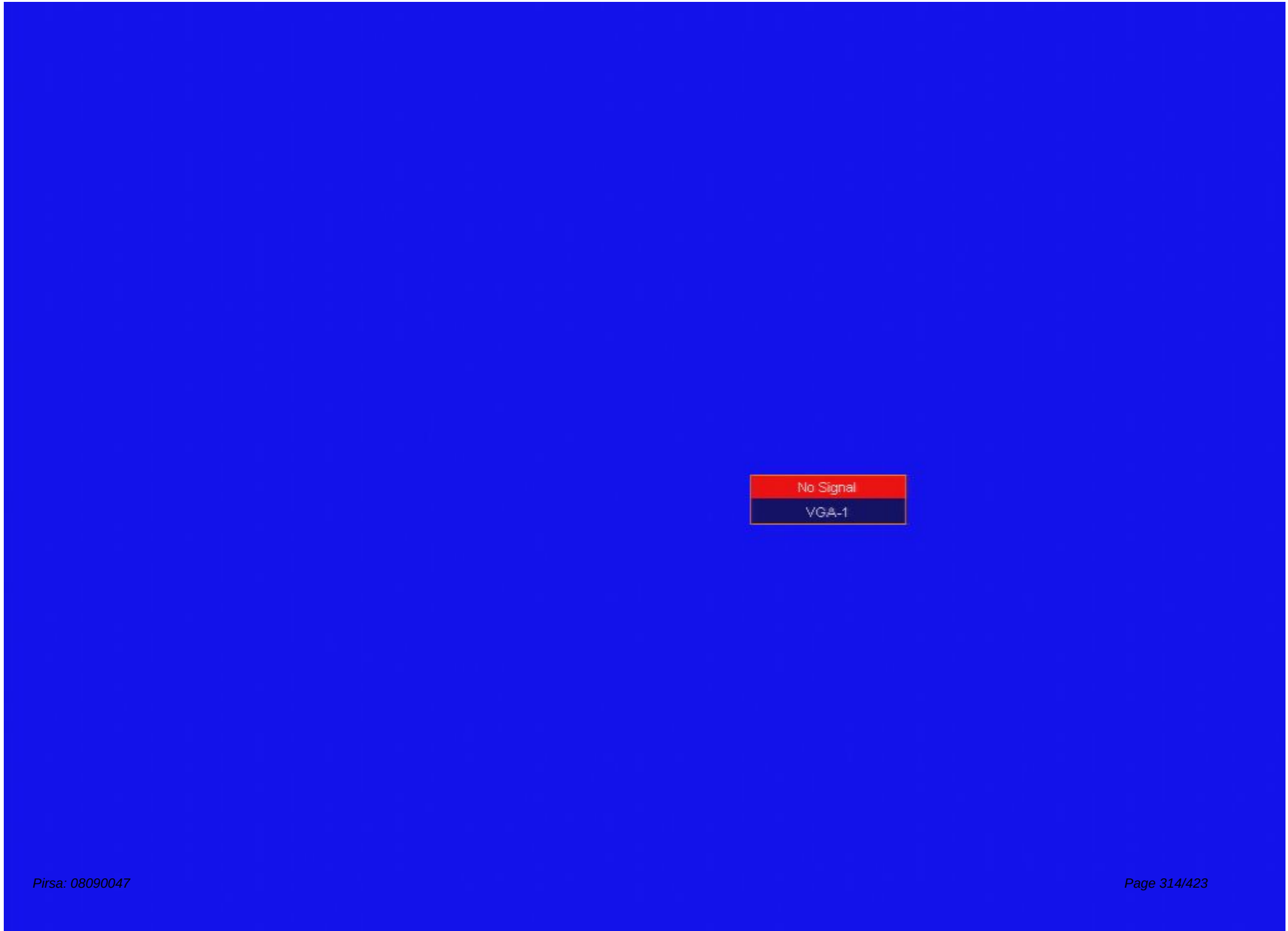

No Signal
VGA-1

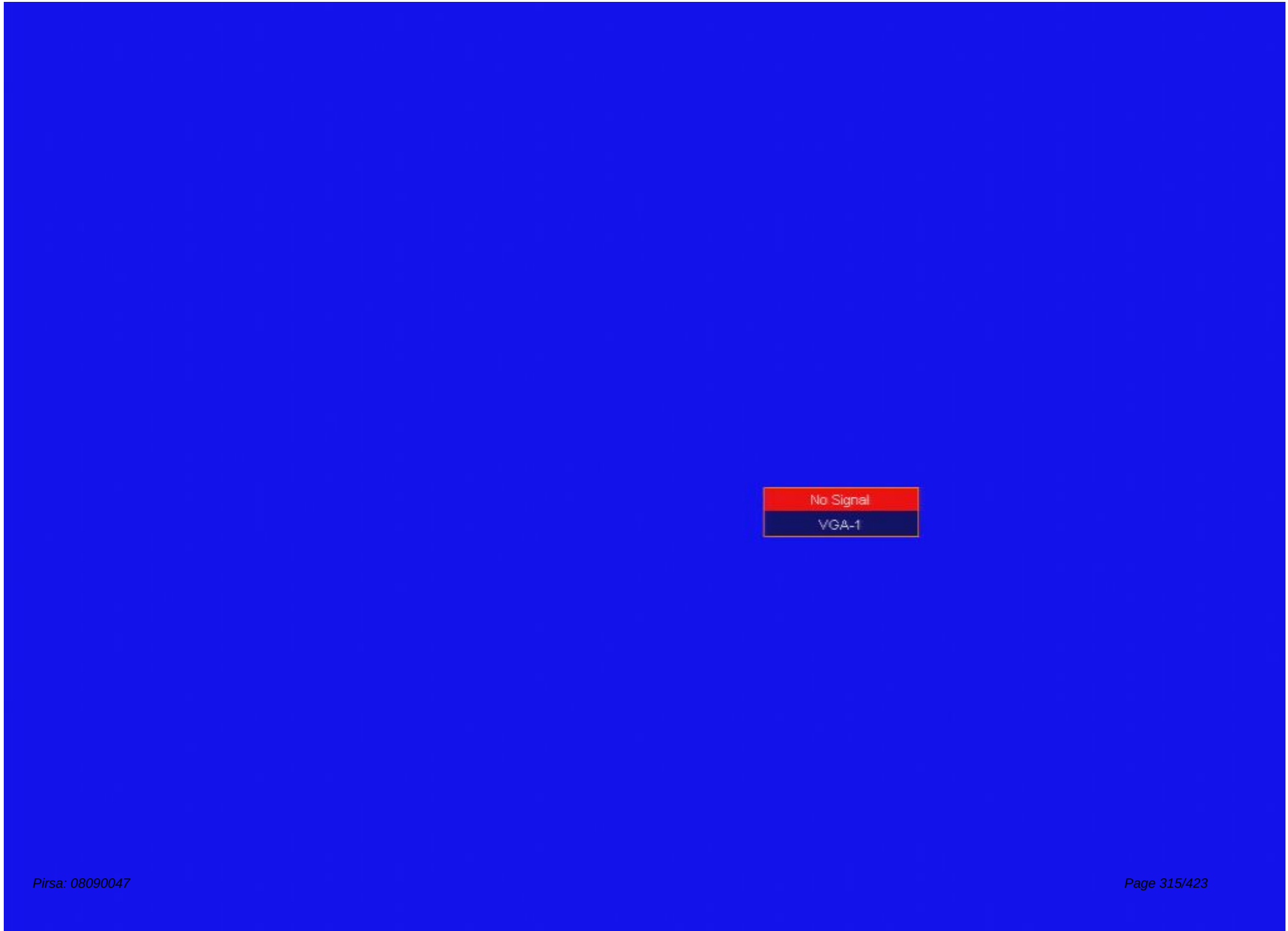

No Signal
VGA-1

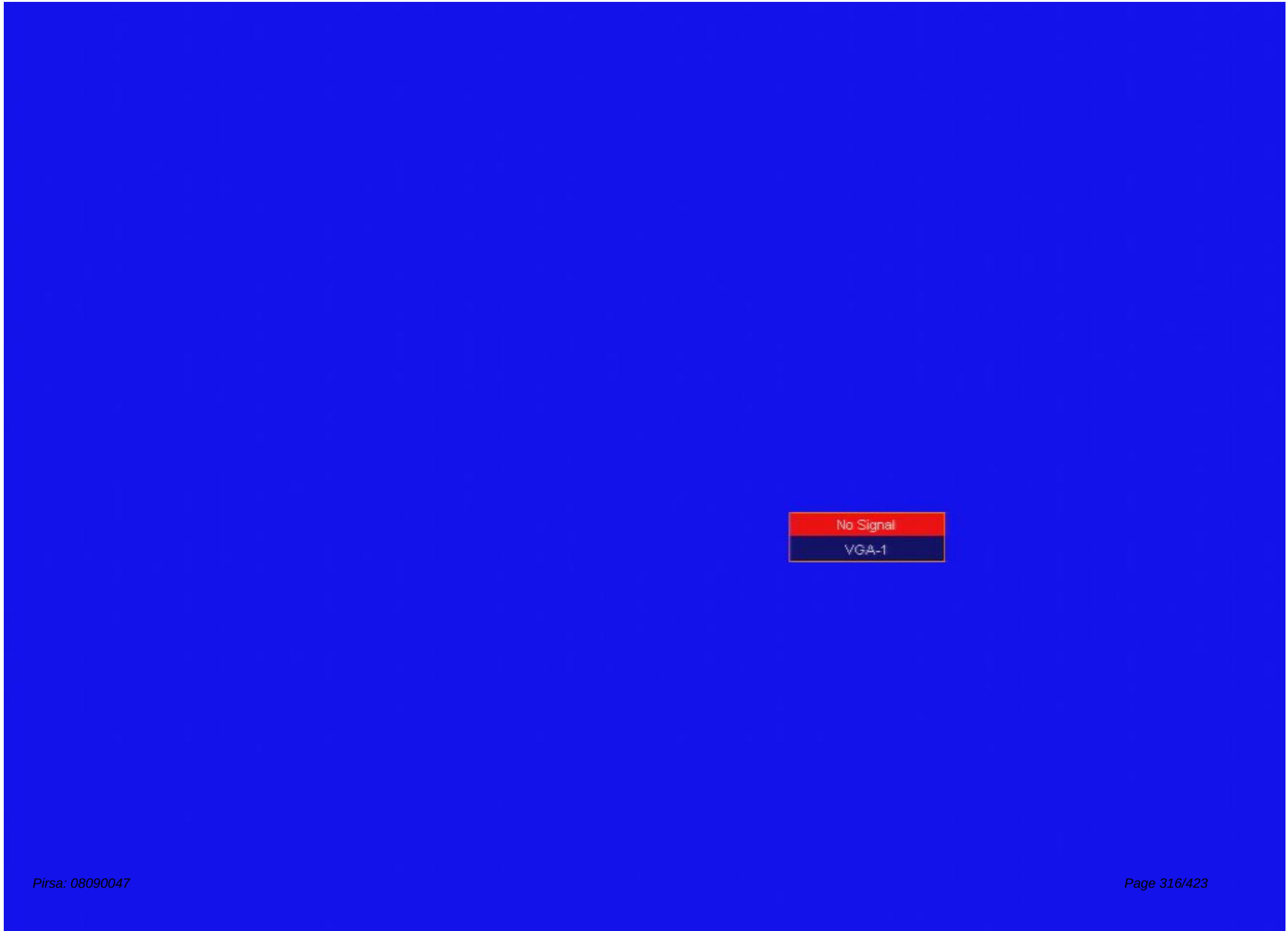

No Signal
VGA-1

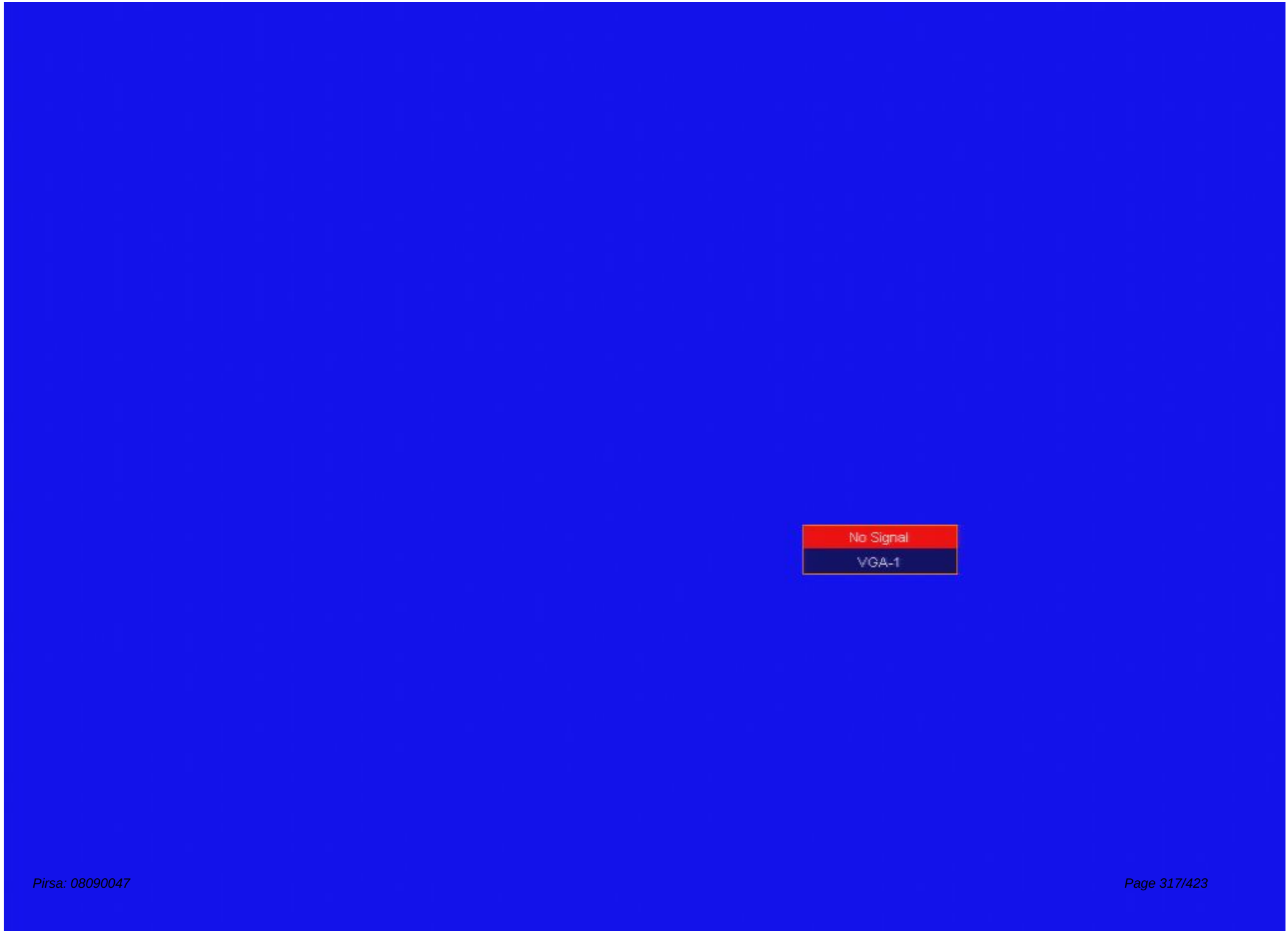

No Signal
VGA-1

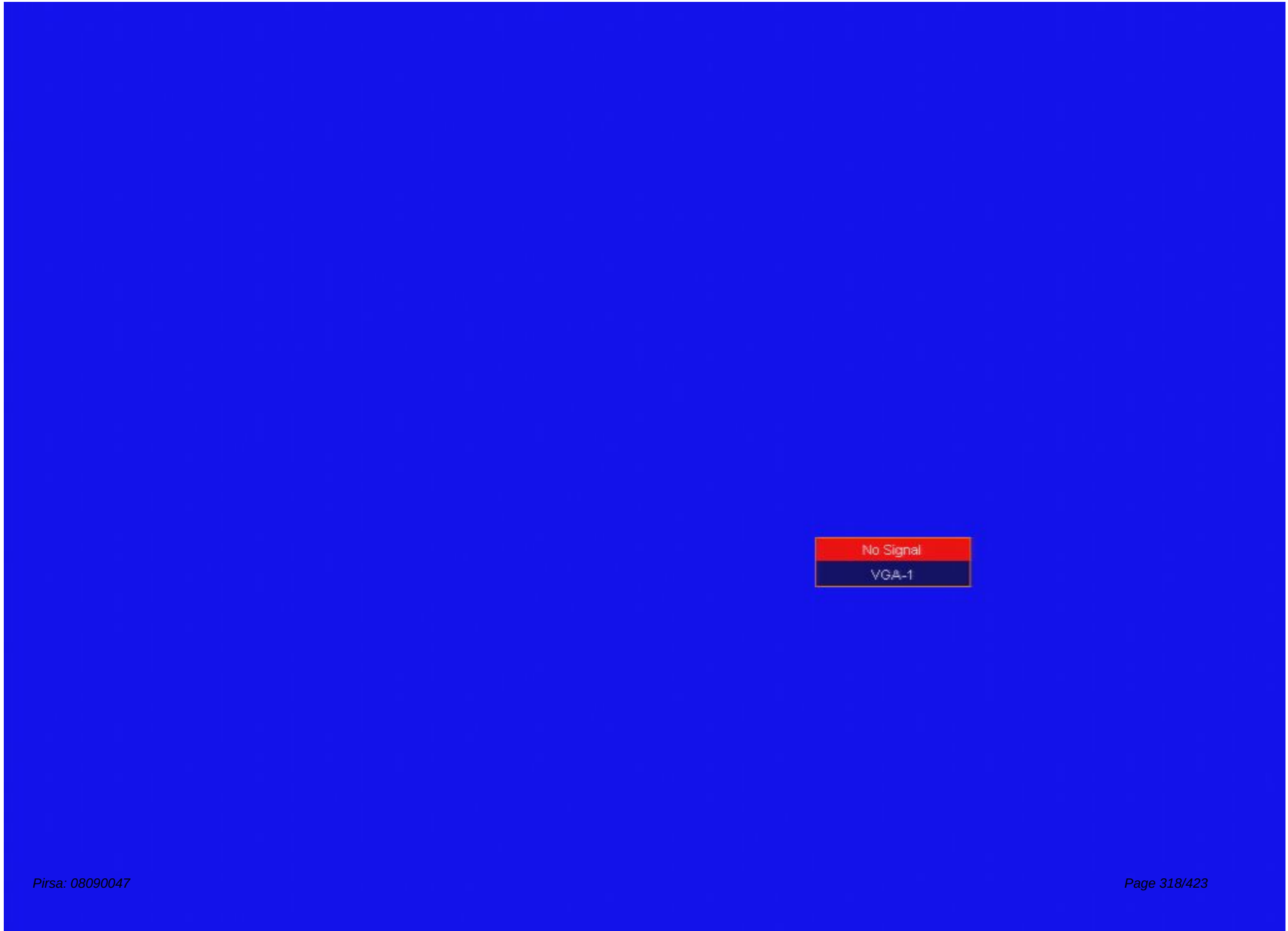

No Signal
VGA-1

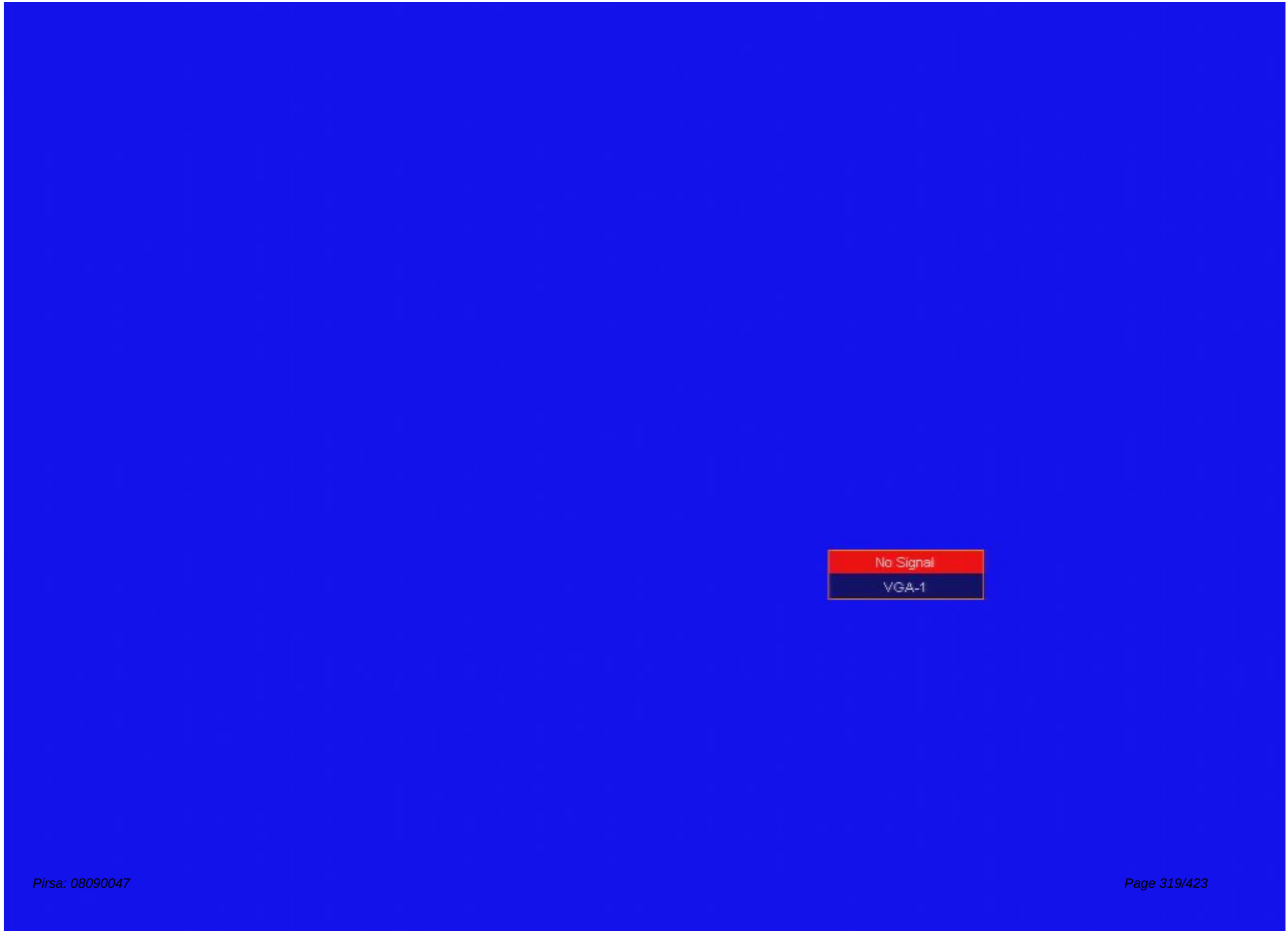

No Signal
VGA-1

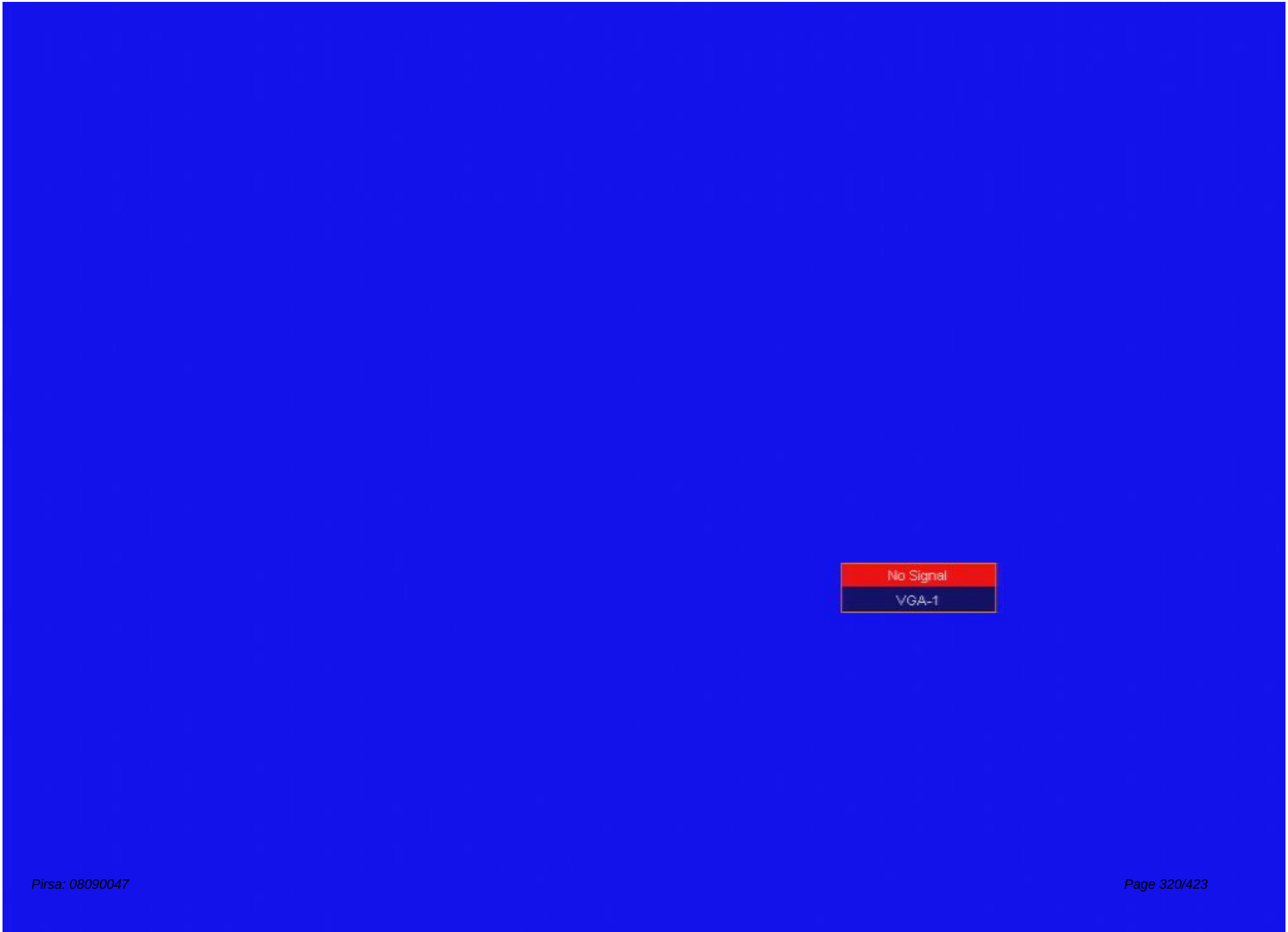

No Signal
VGA-1

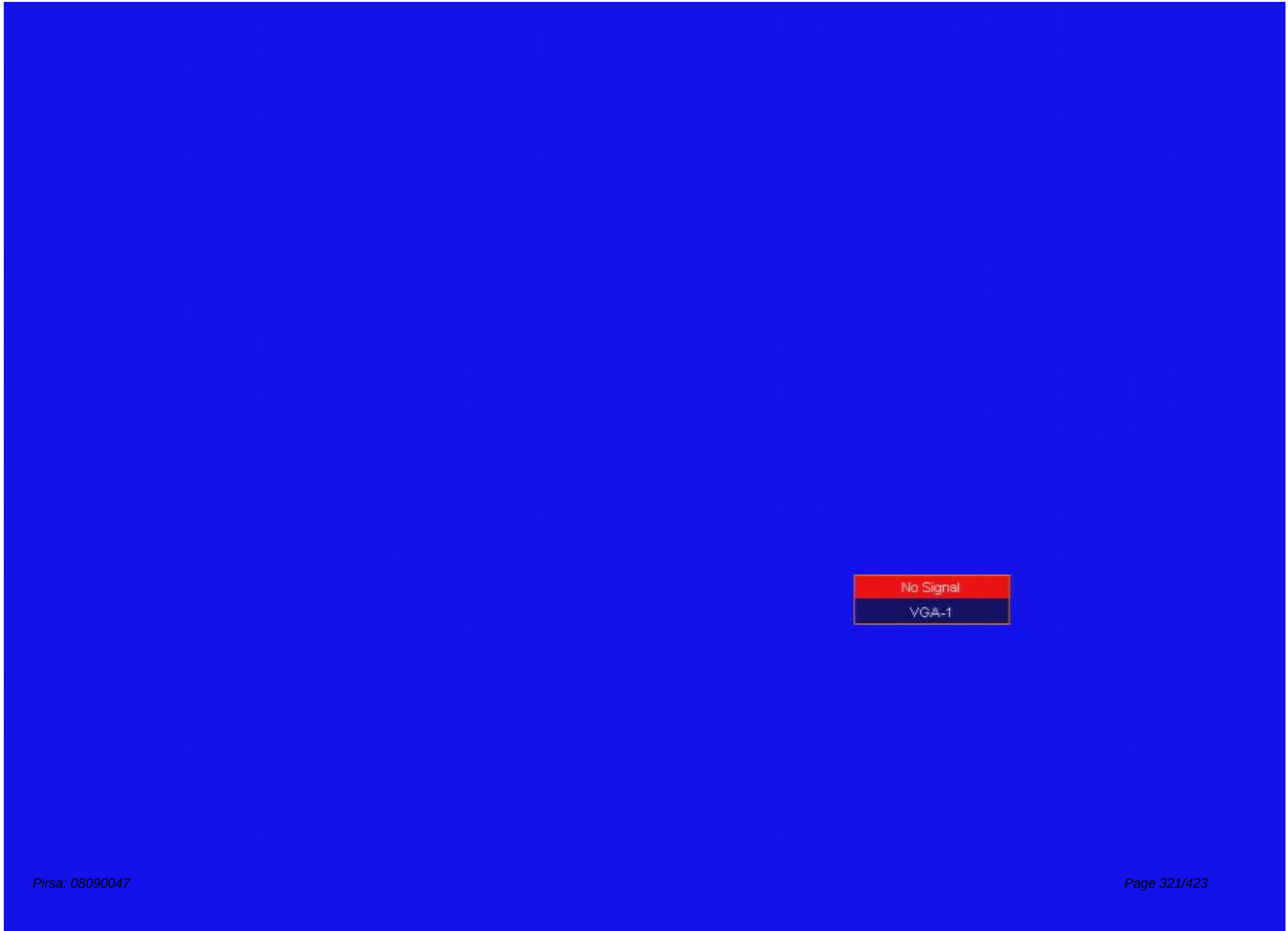

No Signal
VGA-1

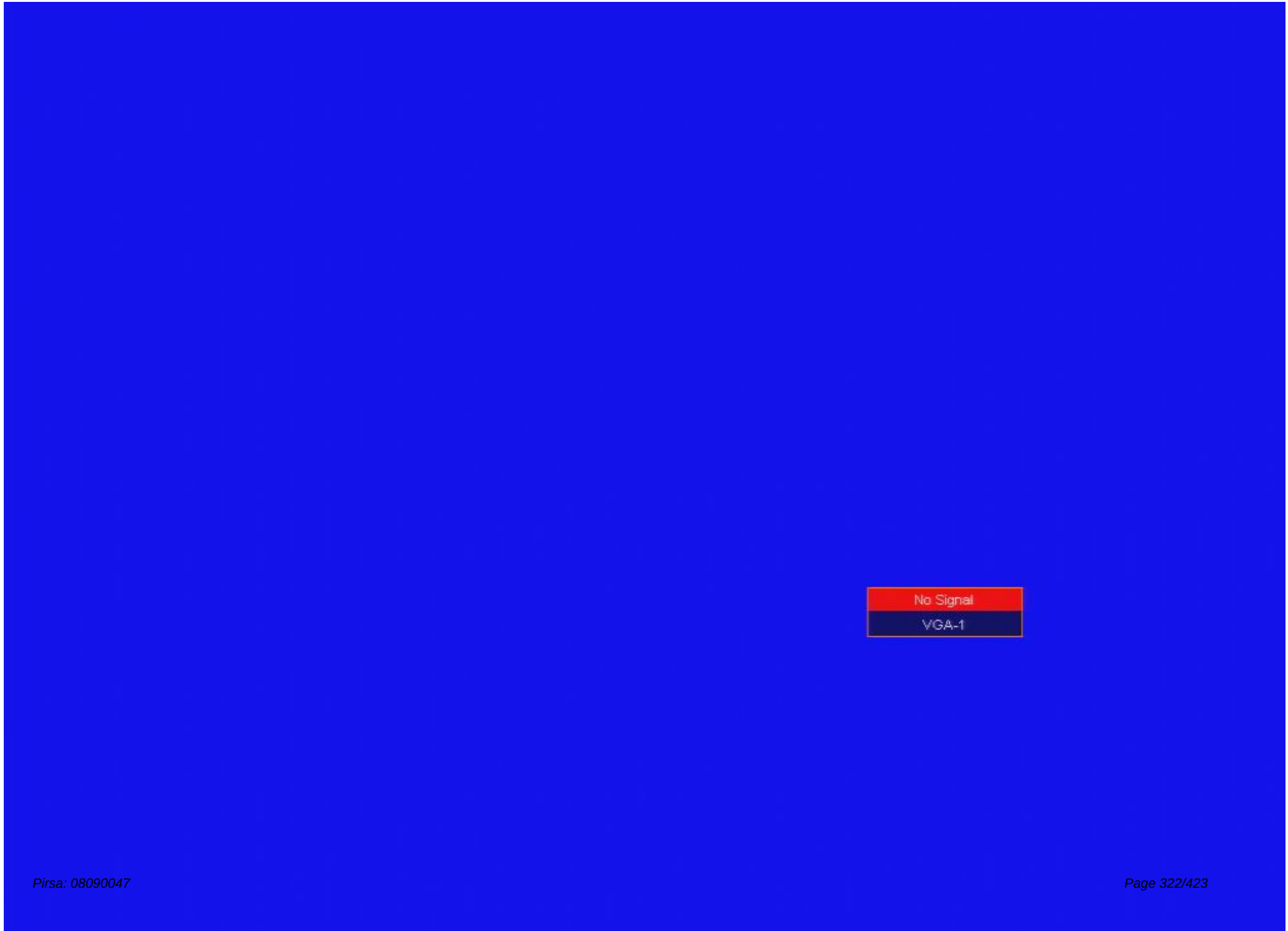

No Signal
VGA-1

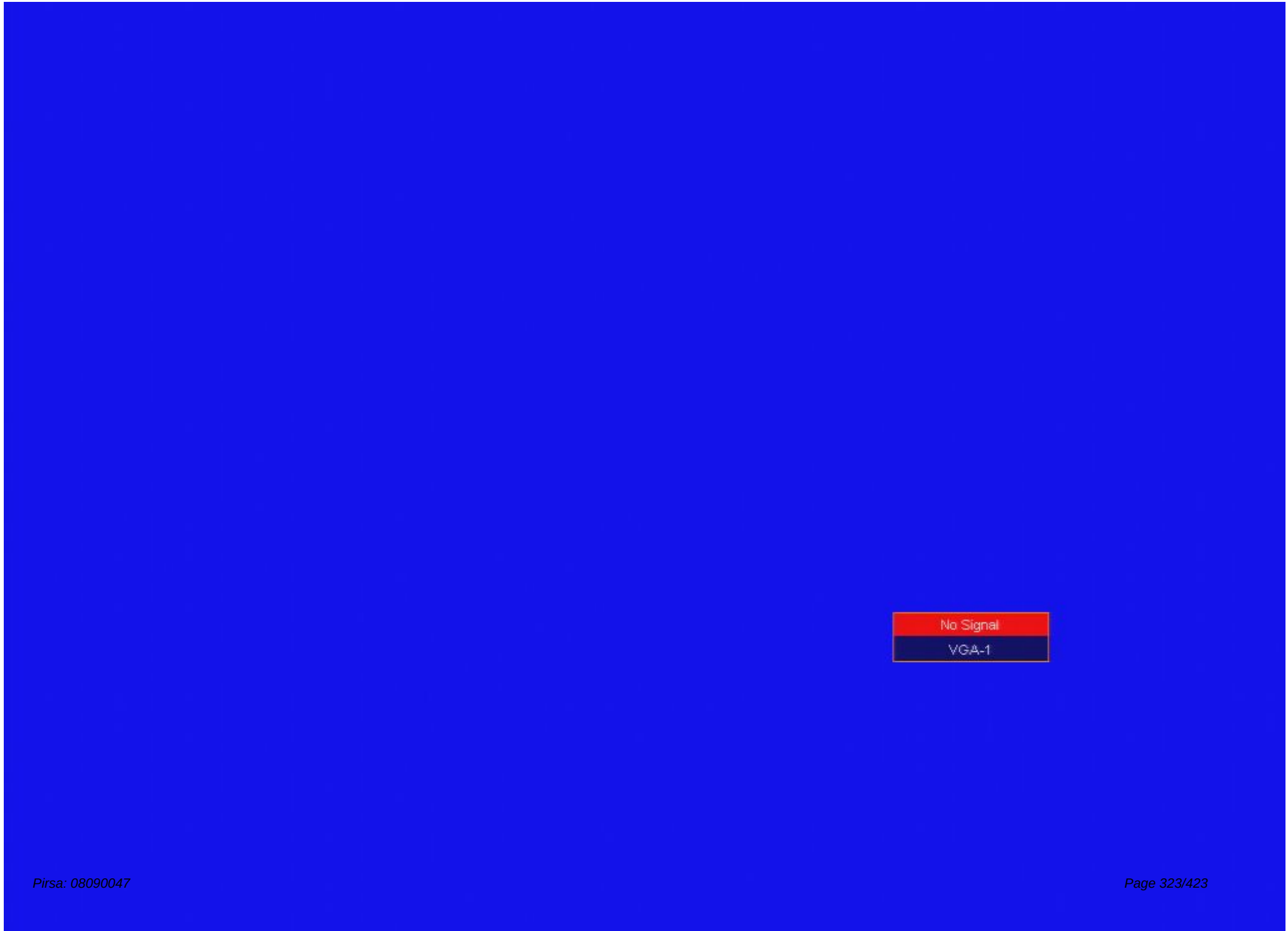

No Signal
VGA-1

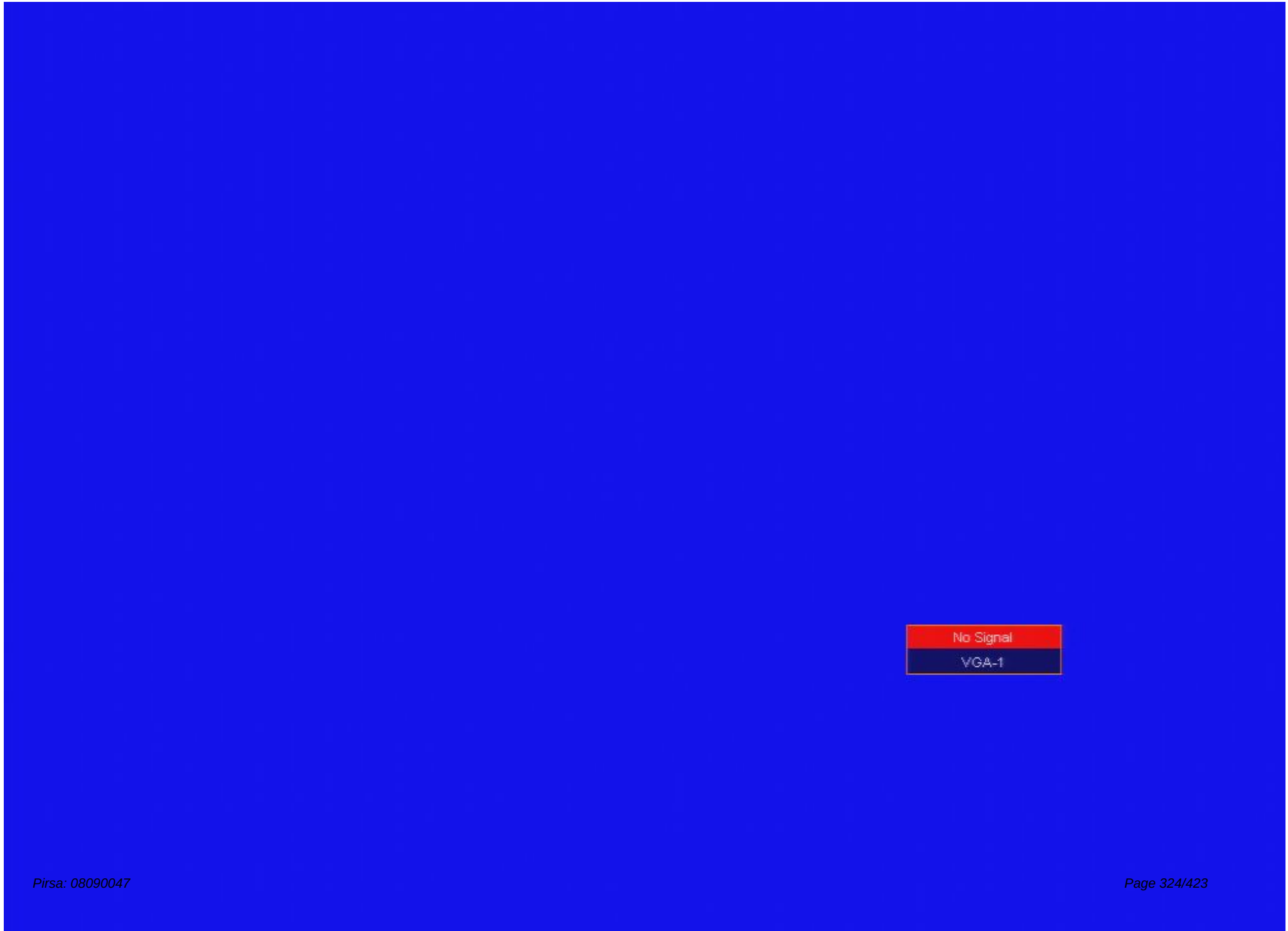

No Signal
VGA-1

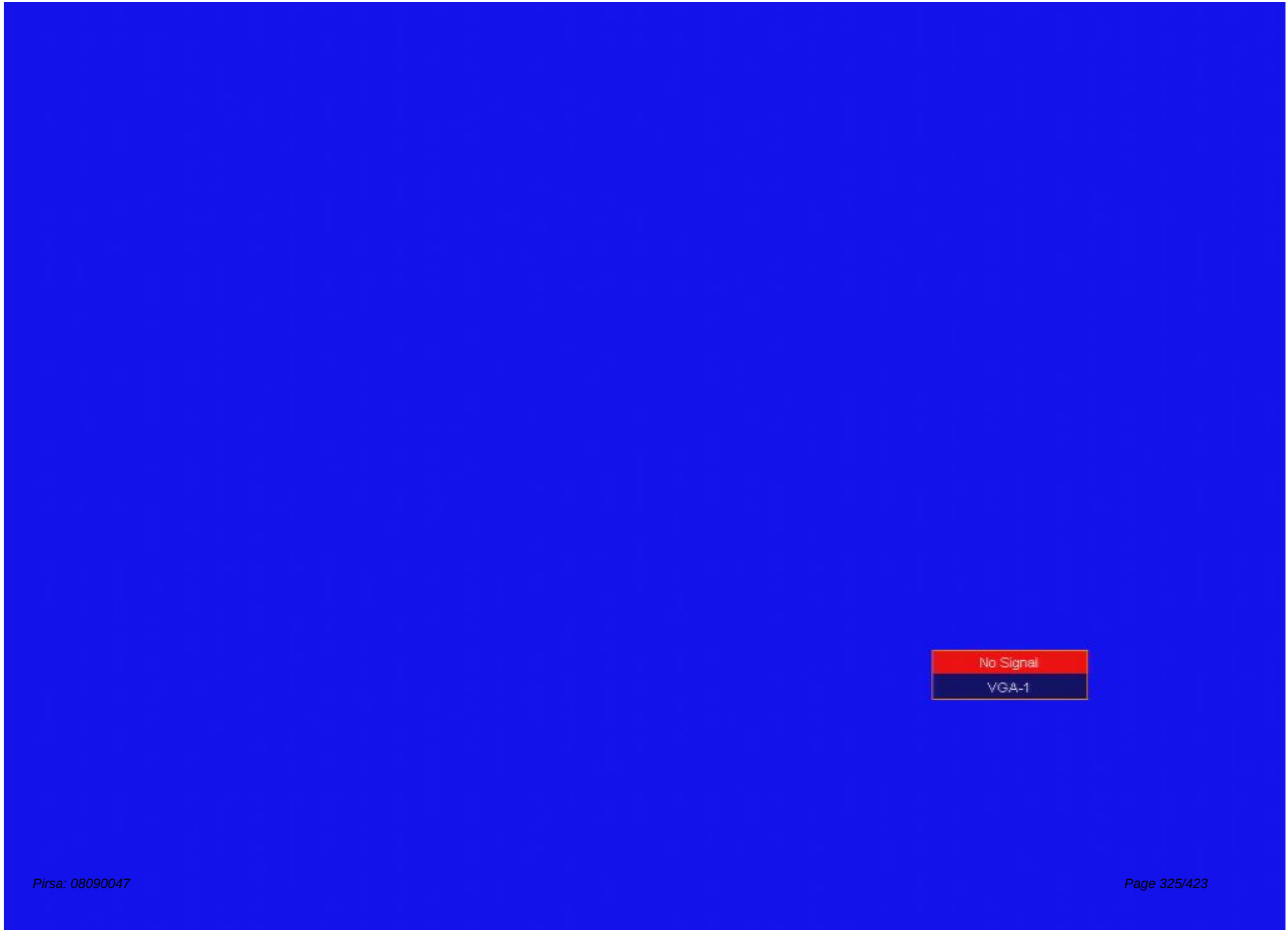

No Signal
VGA-1

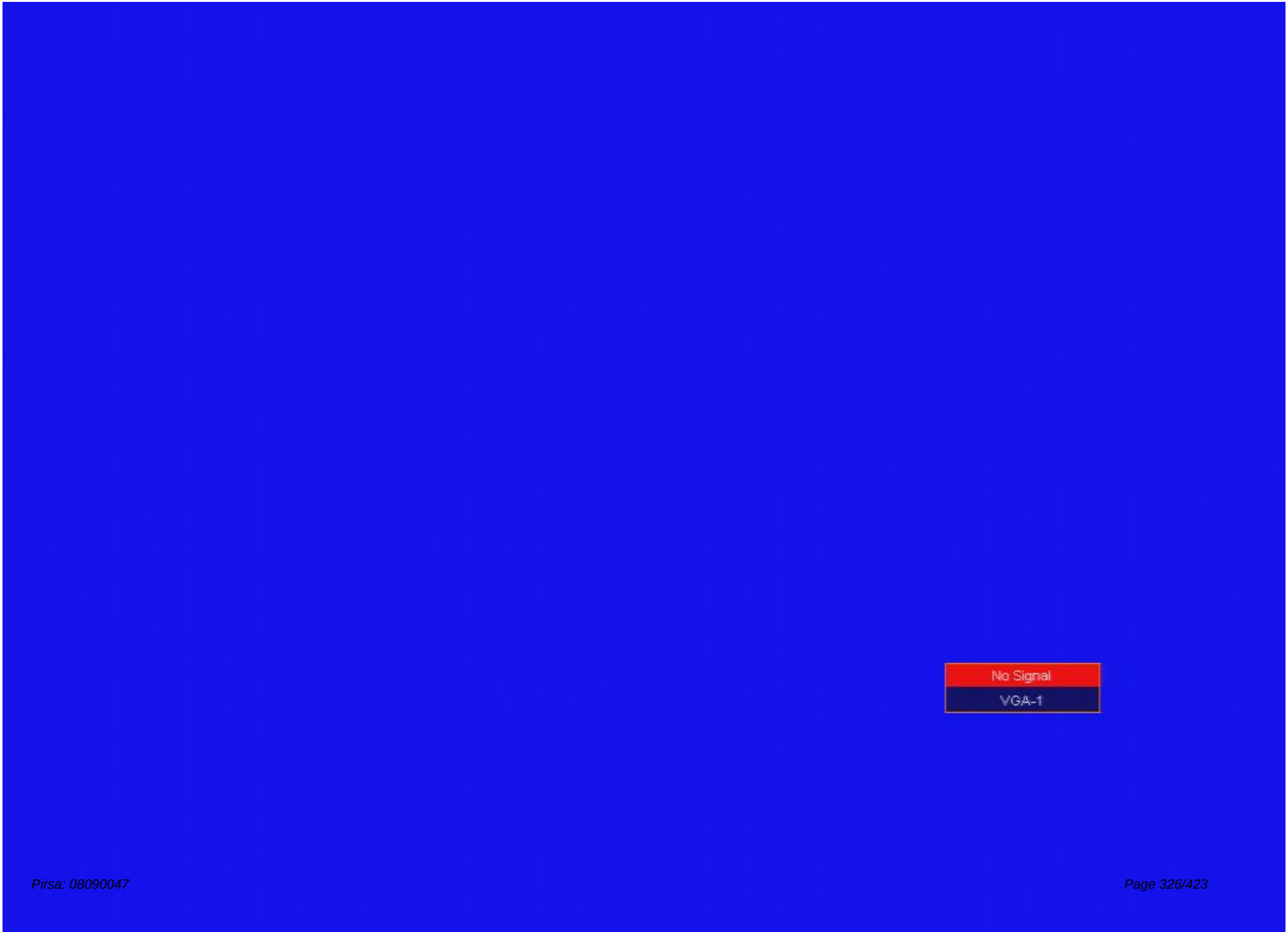

No Signal
VGA-1

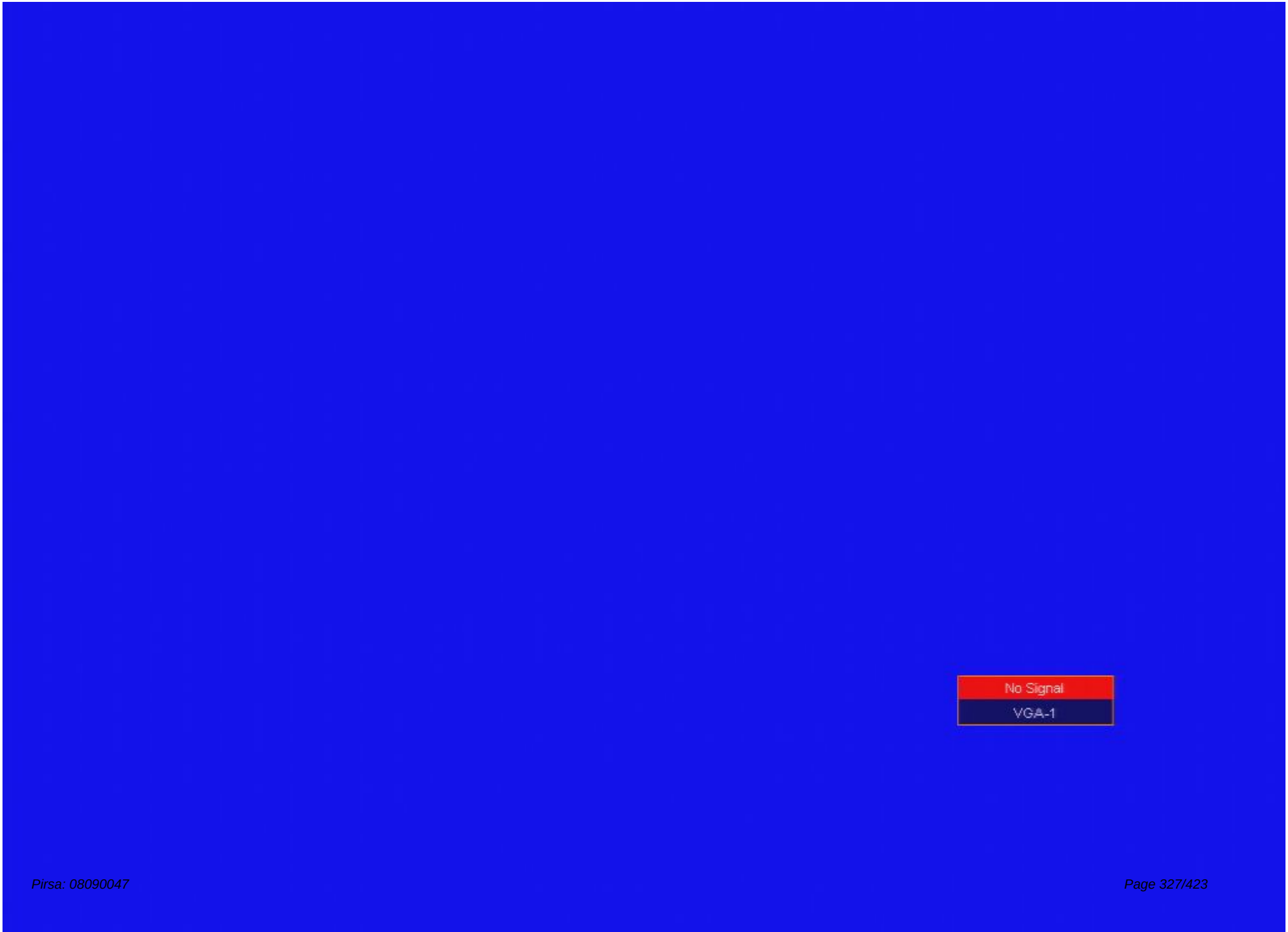

No Signal
VGA-1

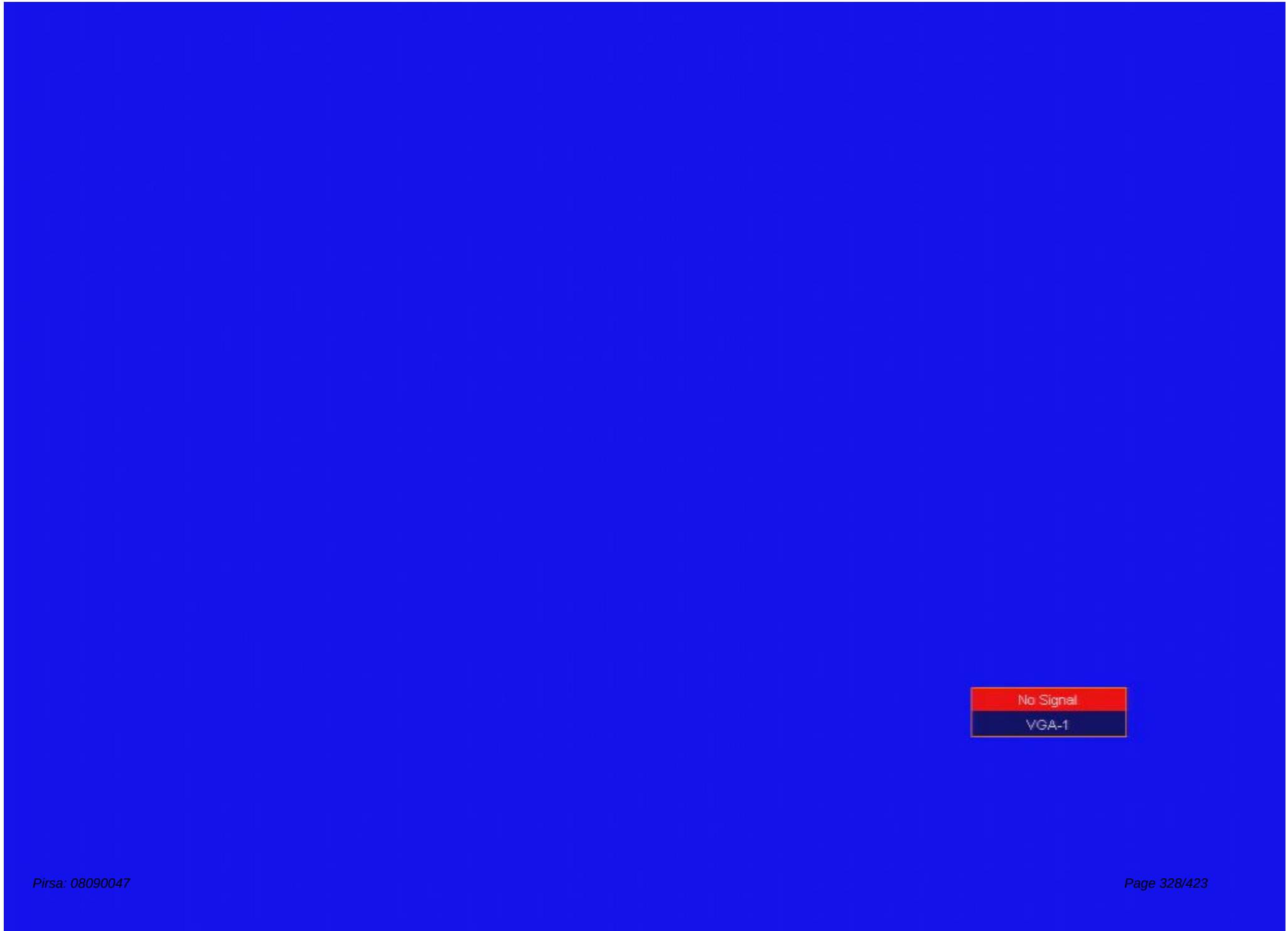

No Signal
VGA-1

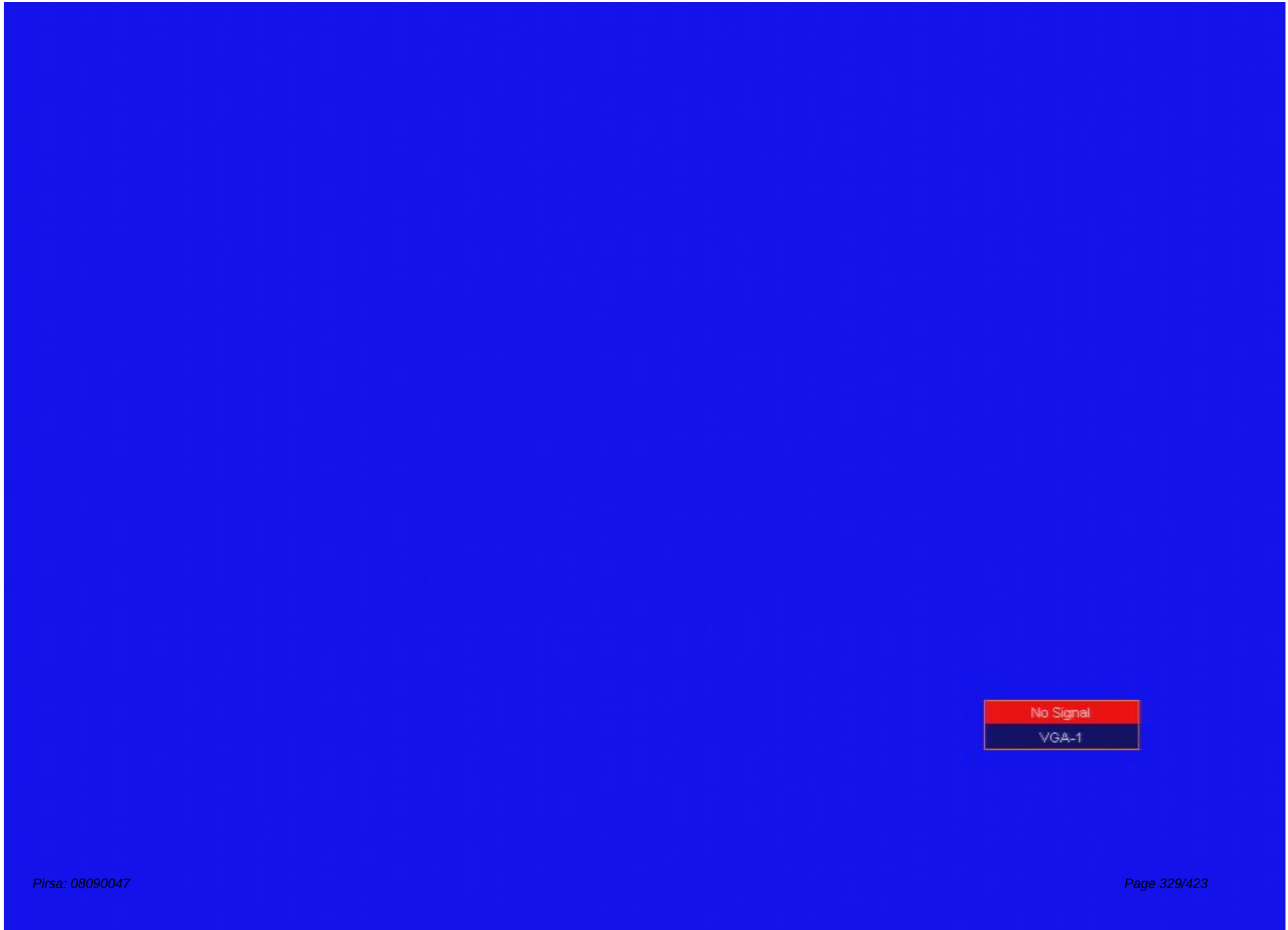

No Signal
VGA-1

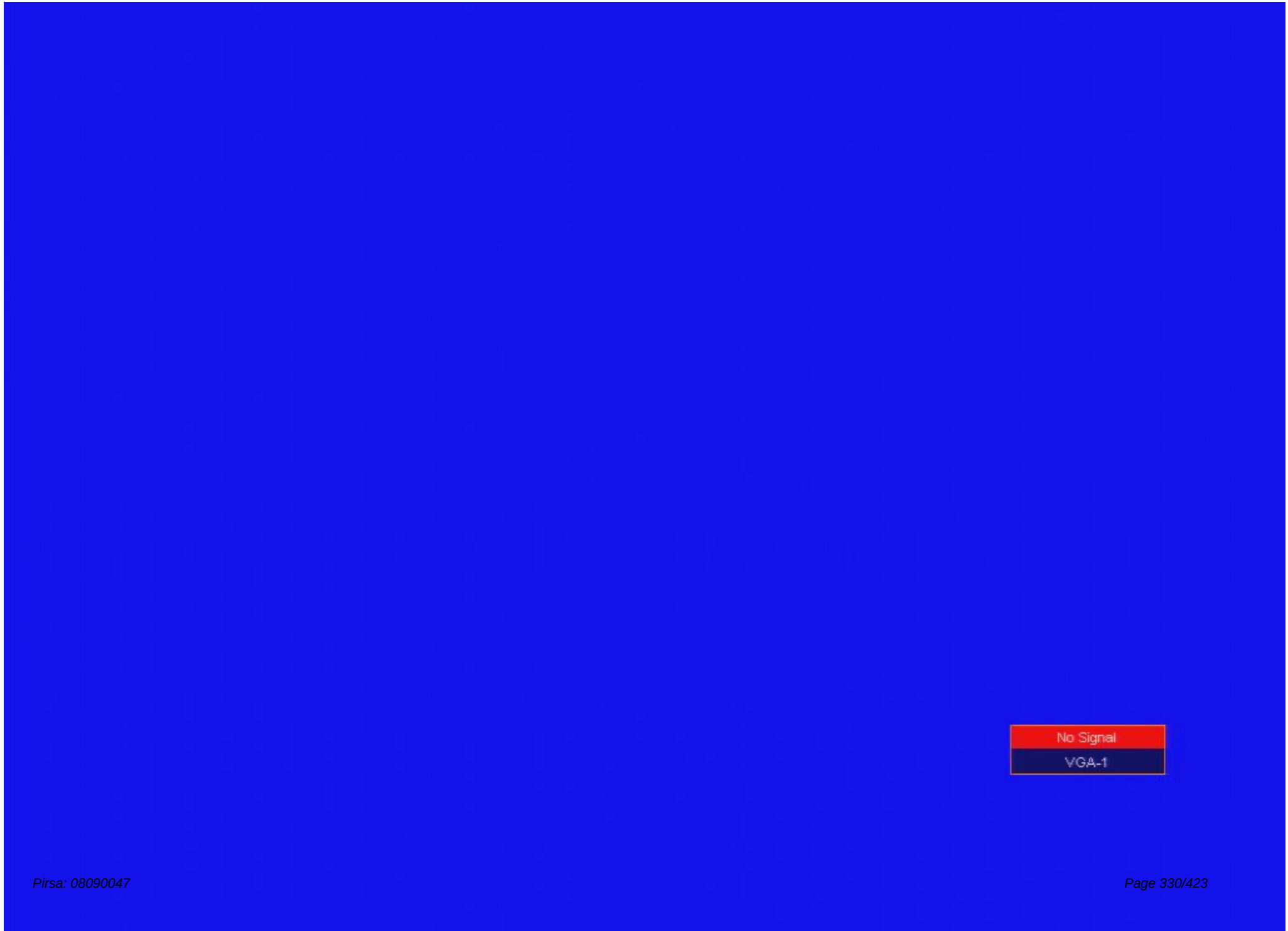

No Signal
VGA-1

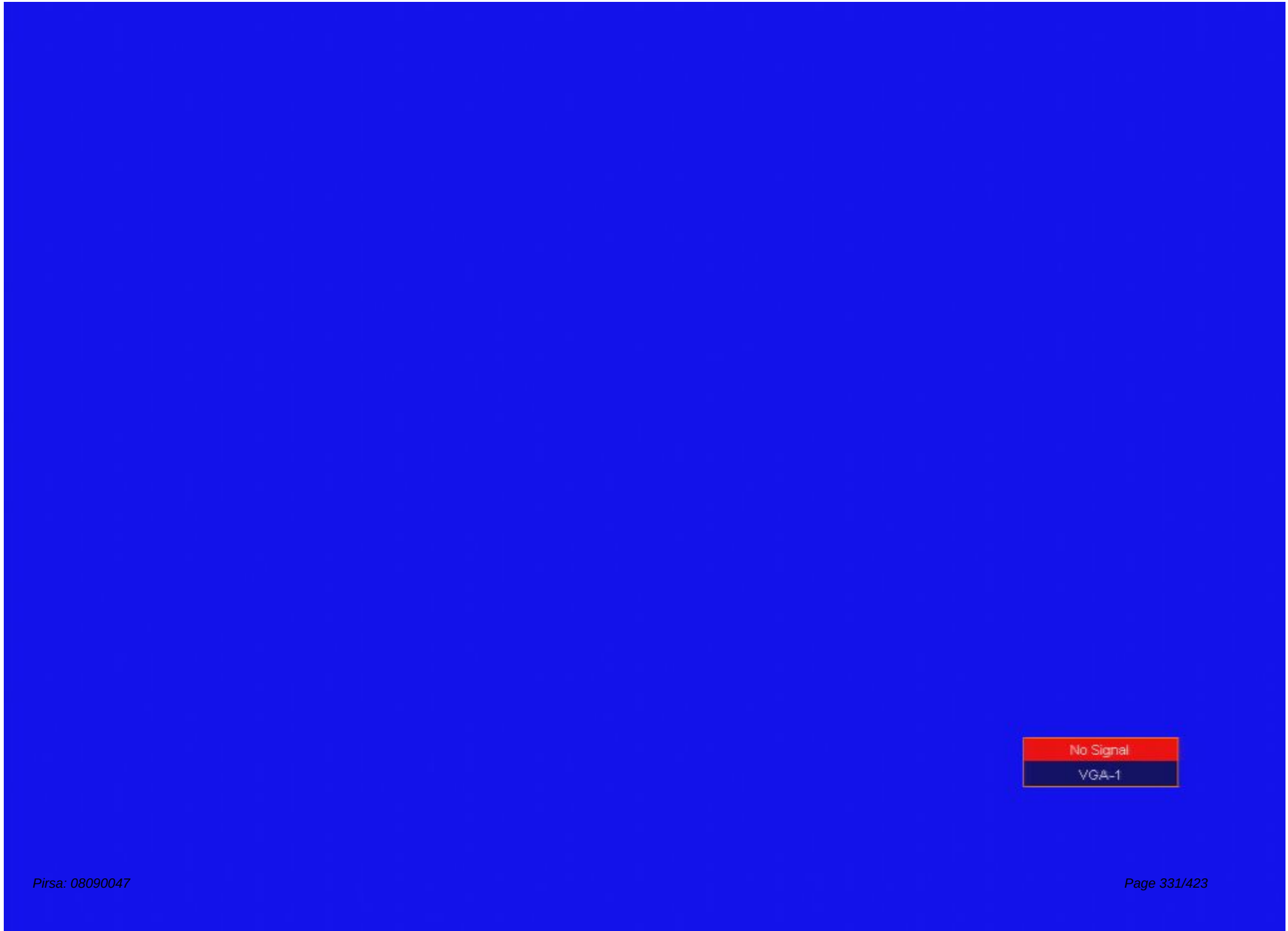

No Signal
VGA-1

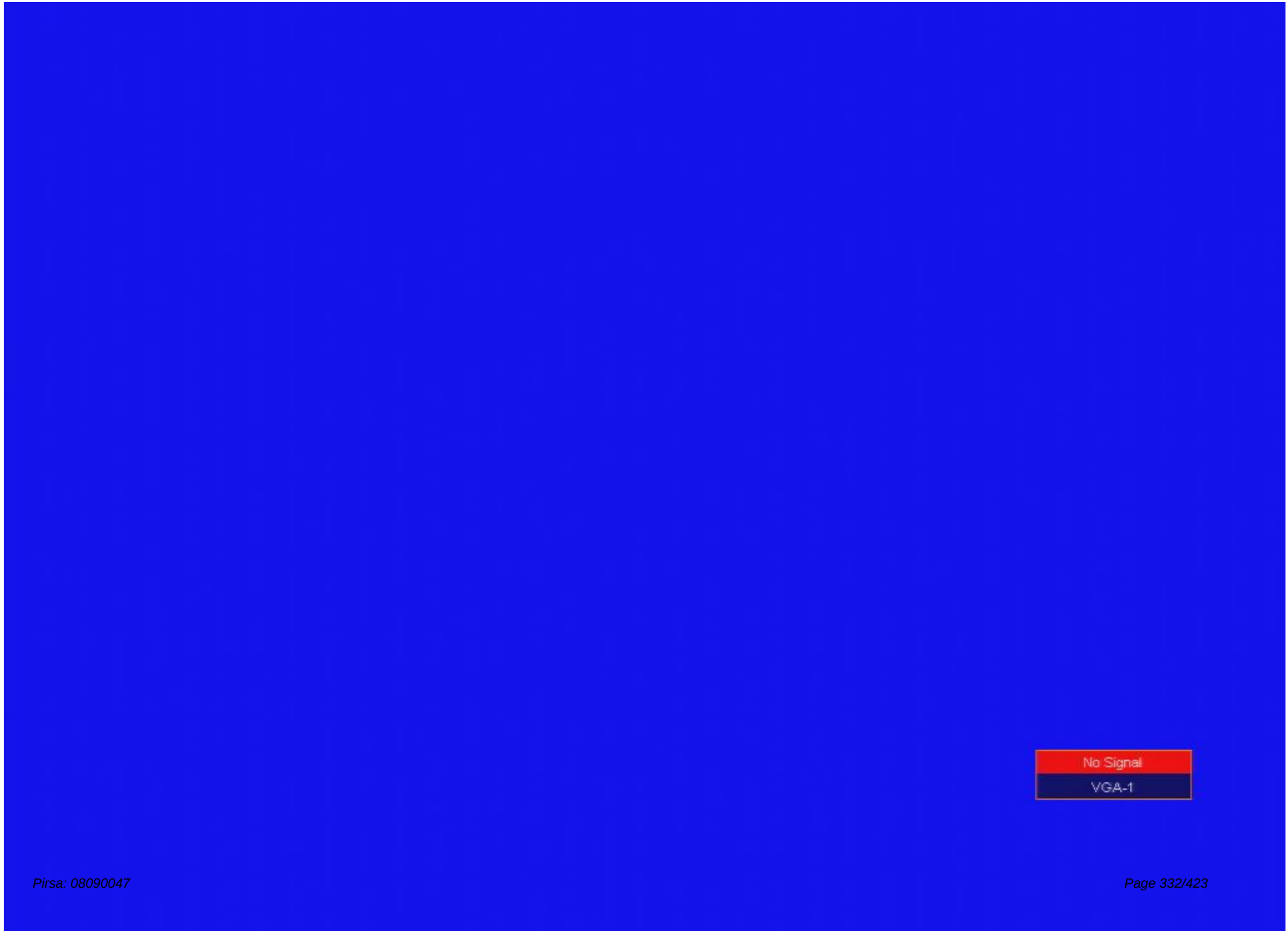

No Signal
VGA-1

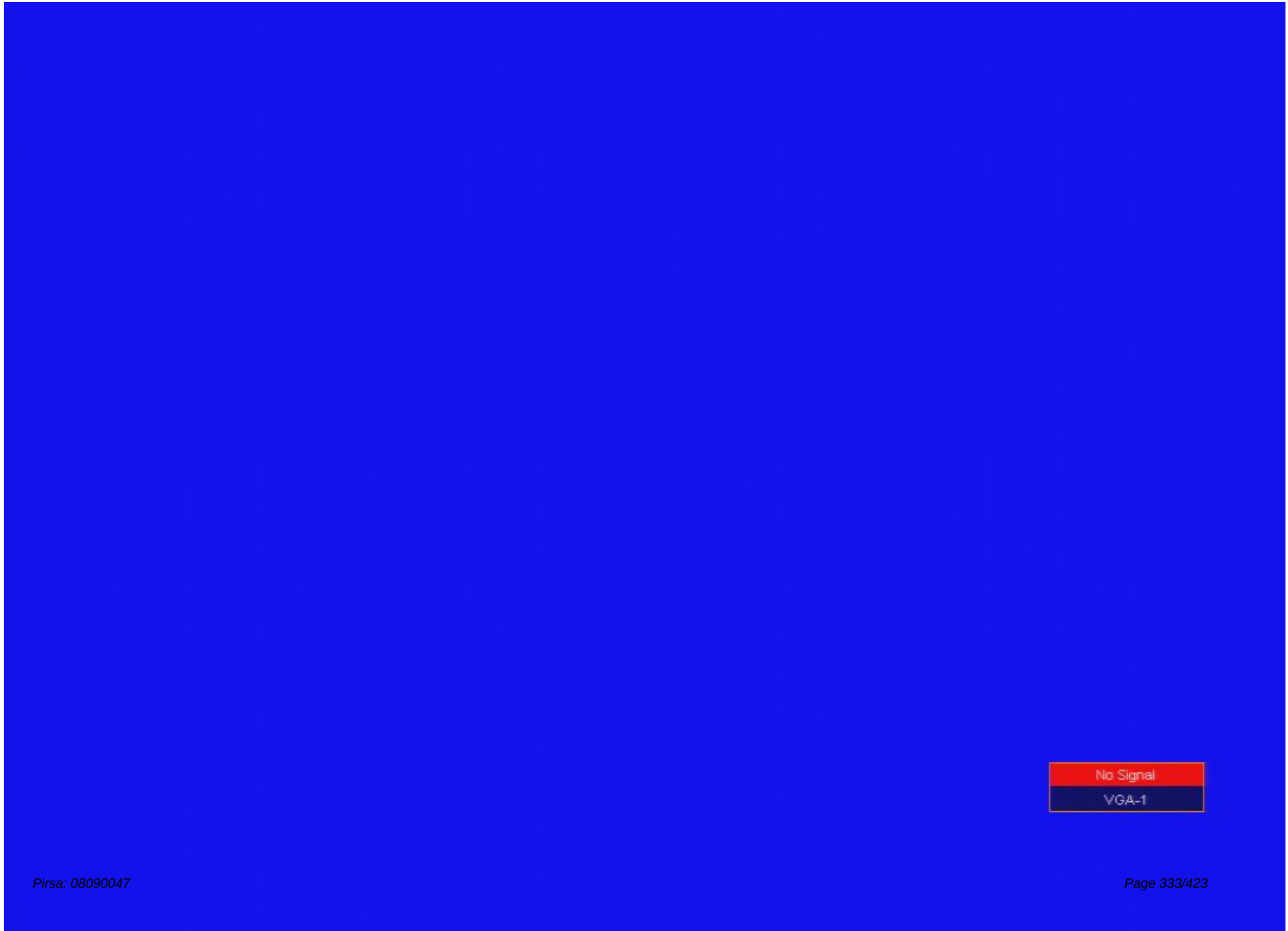

No Signal
VGA-1

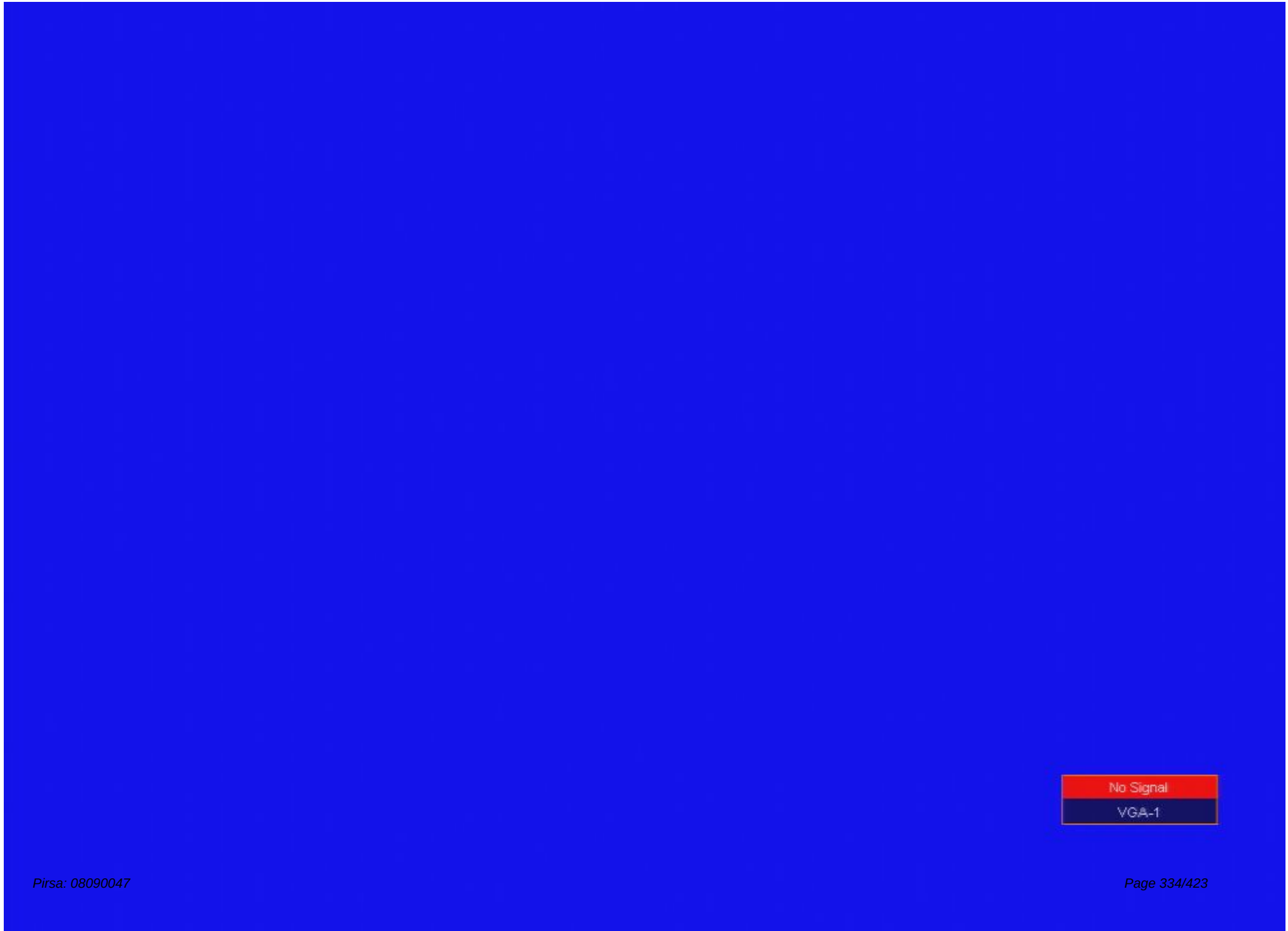

No Signal
VGA-1

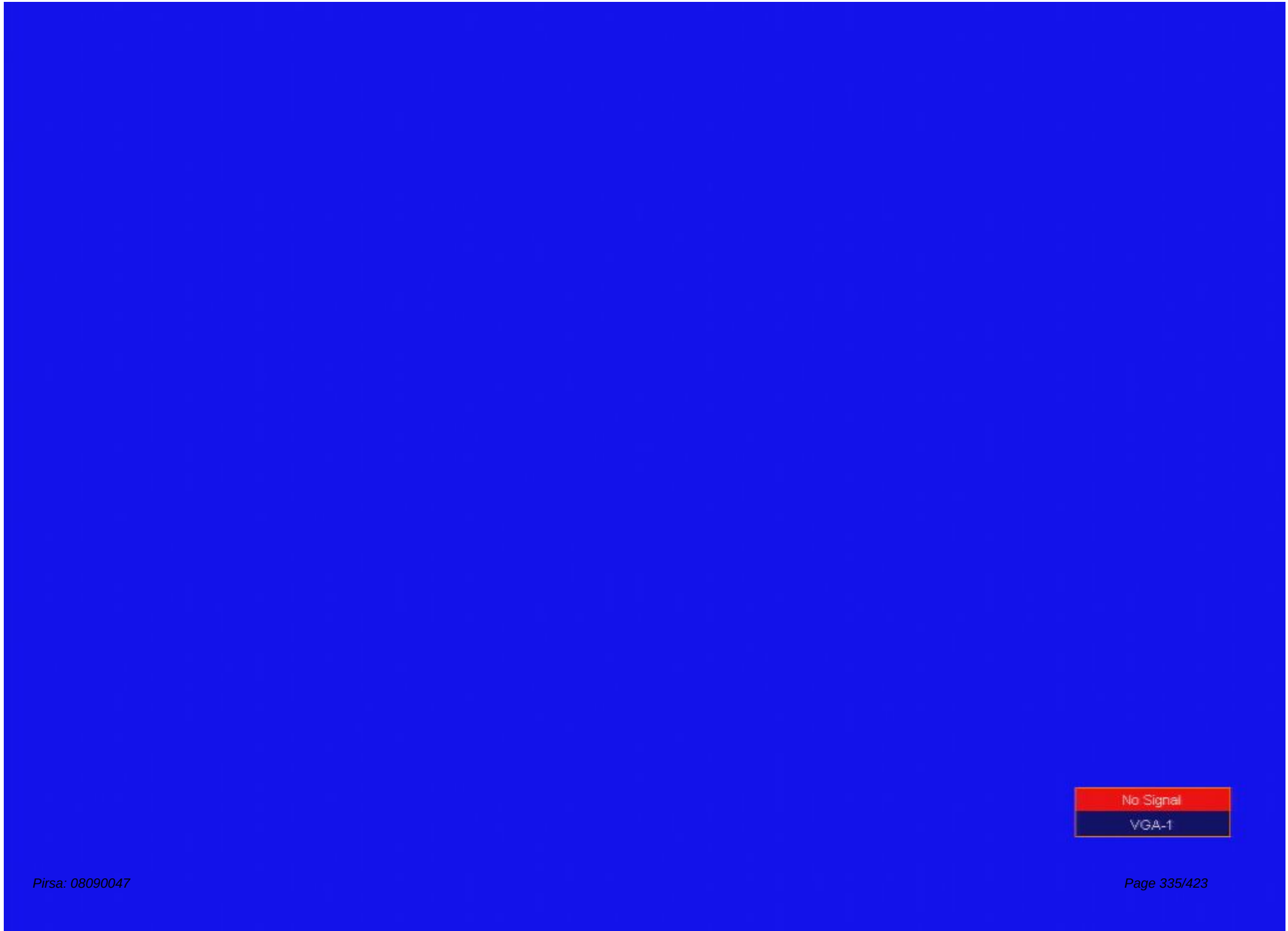

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

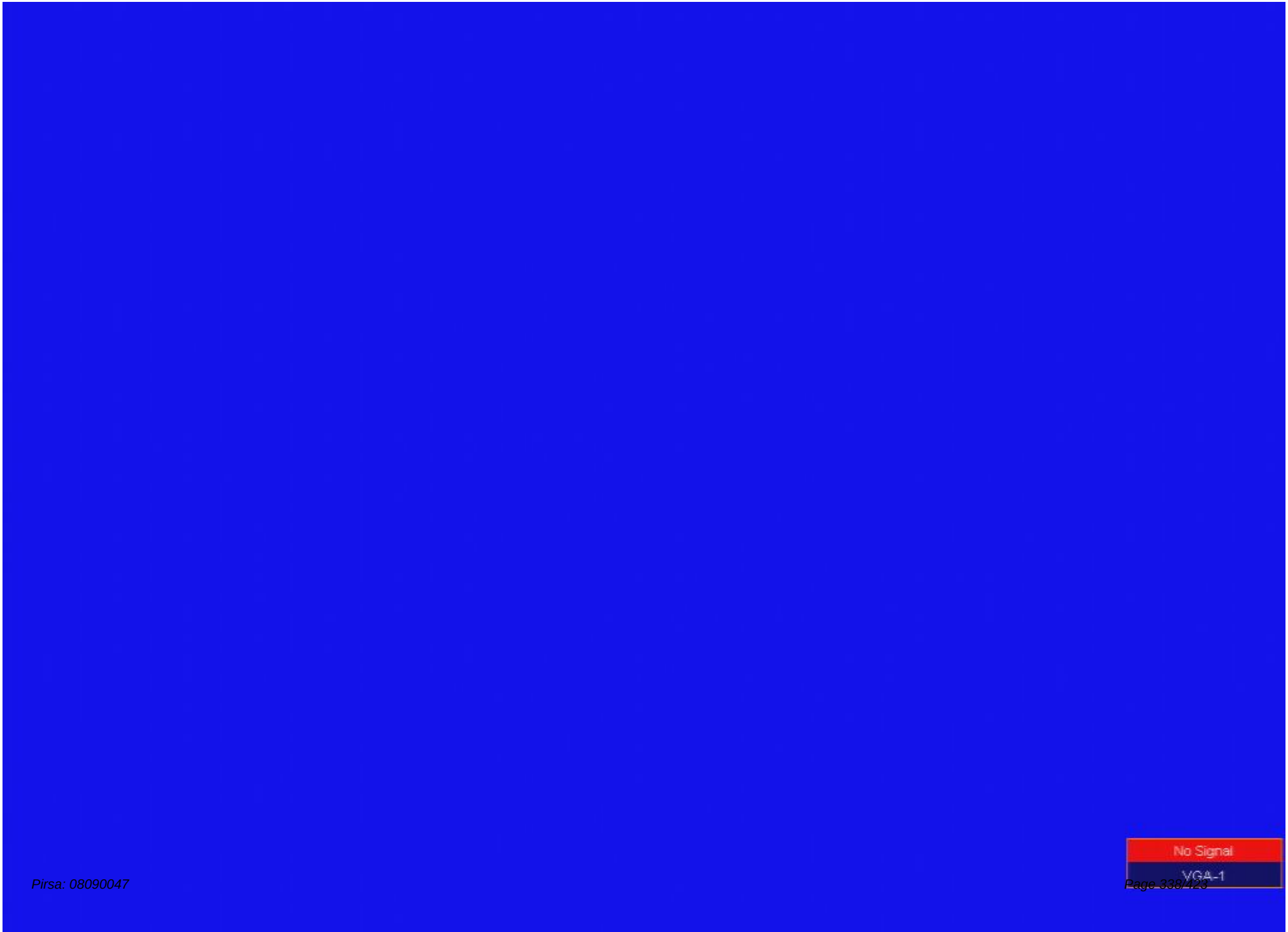

No Signal
VGA-1

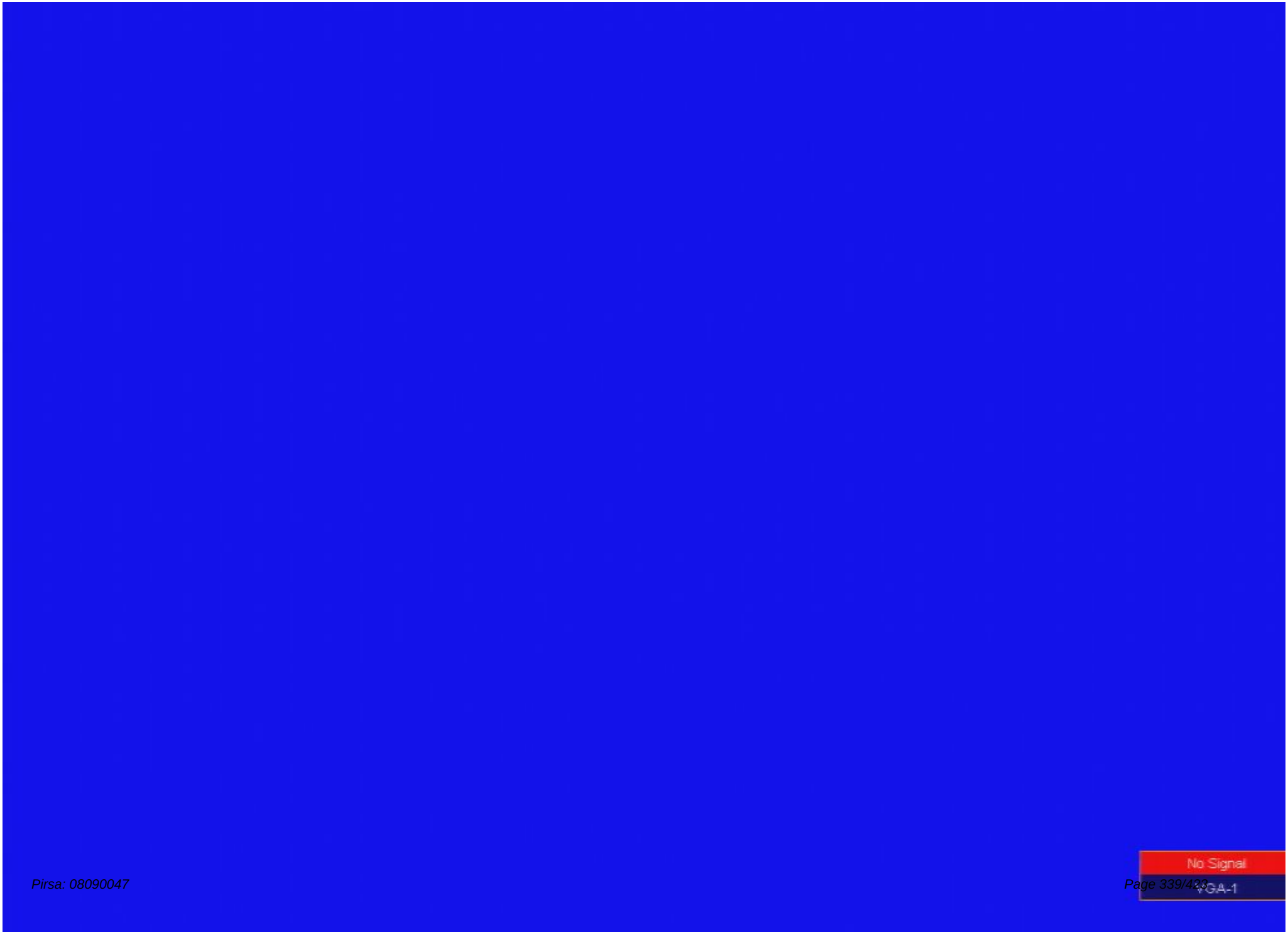

No Signal
VGA-1

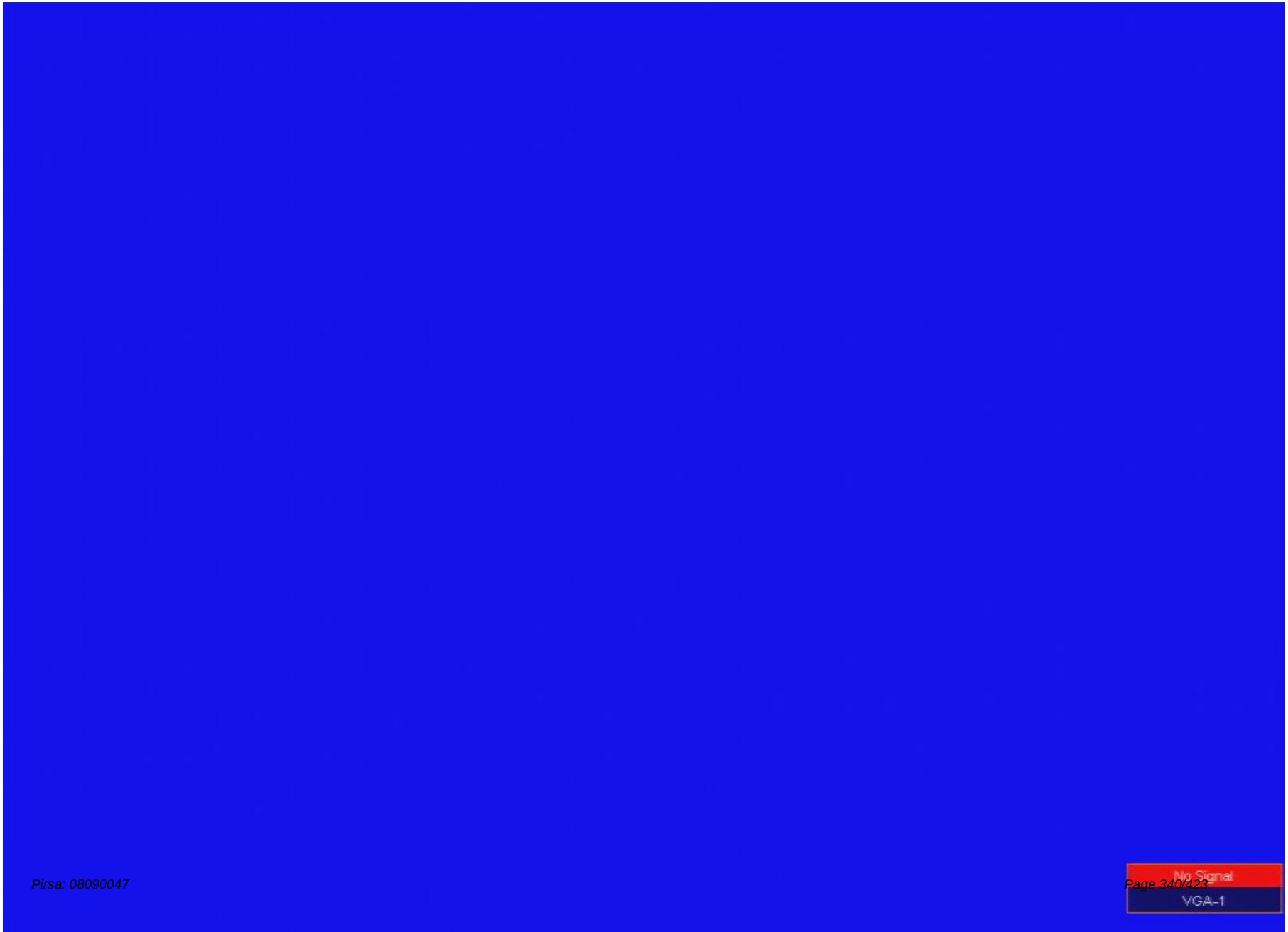

No Signal
VGA-1

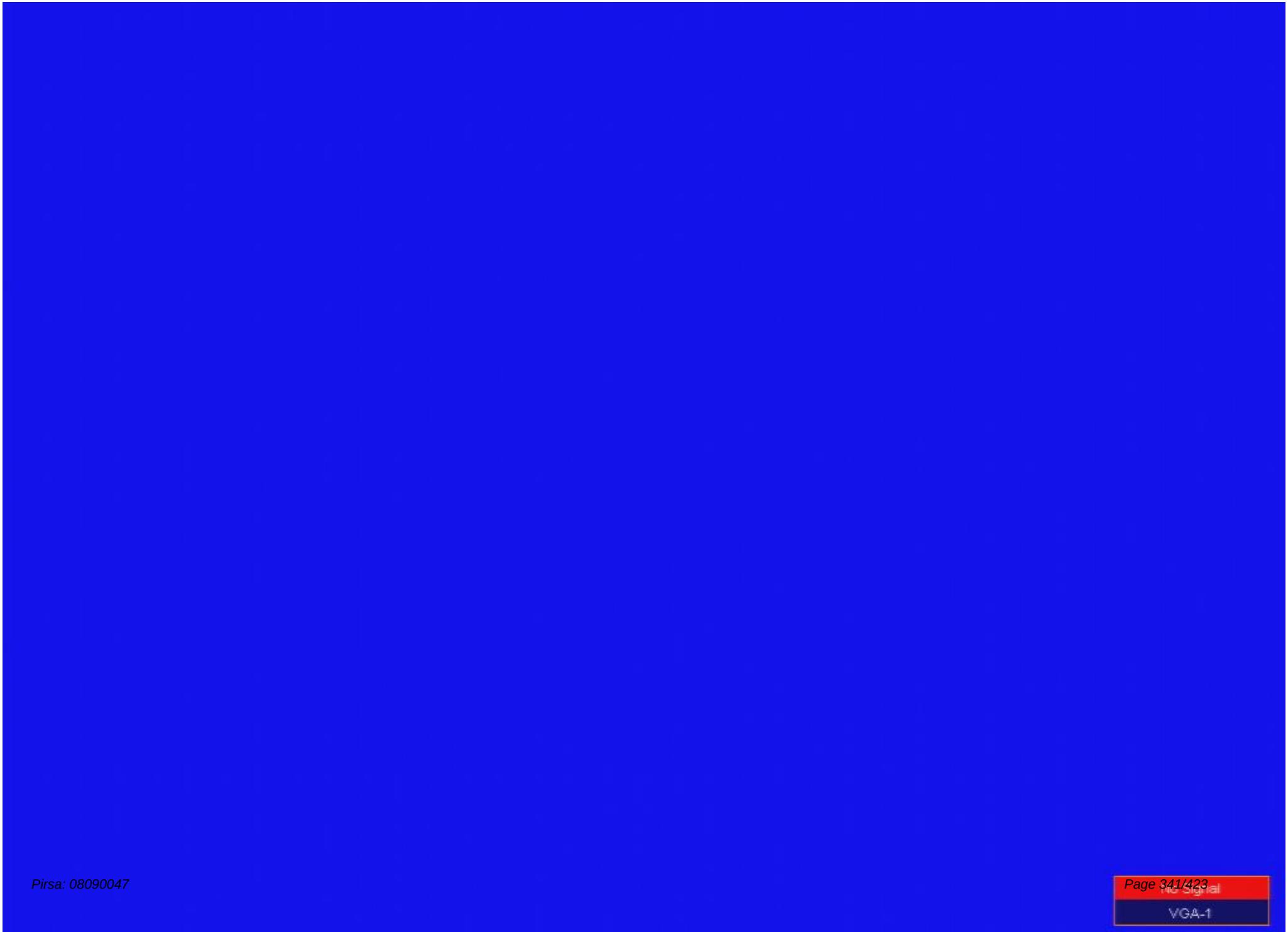

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

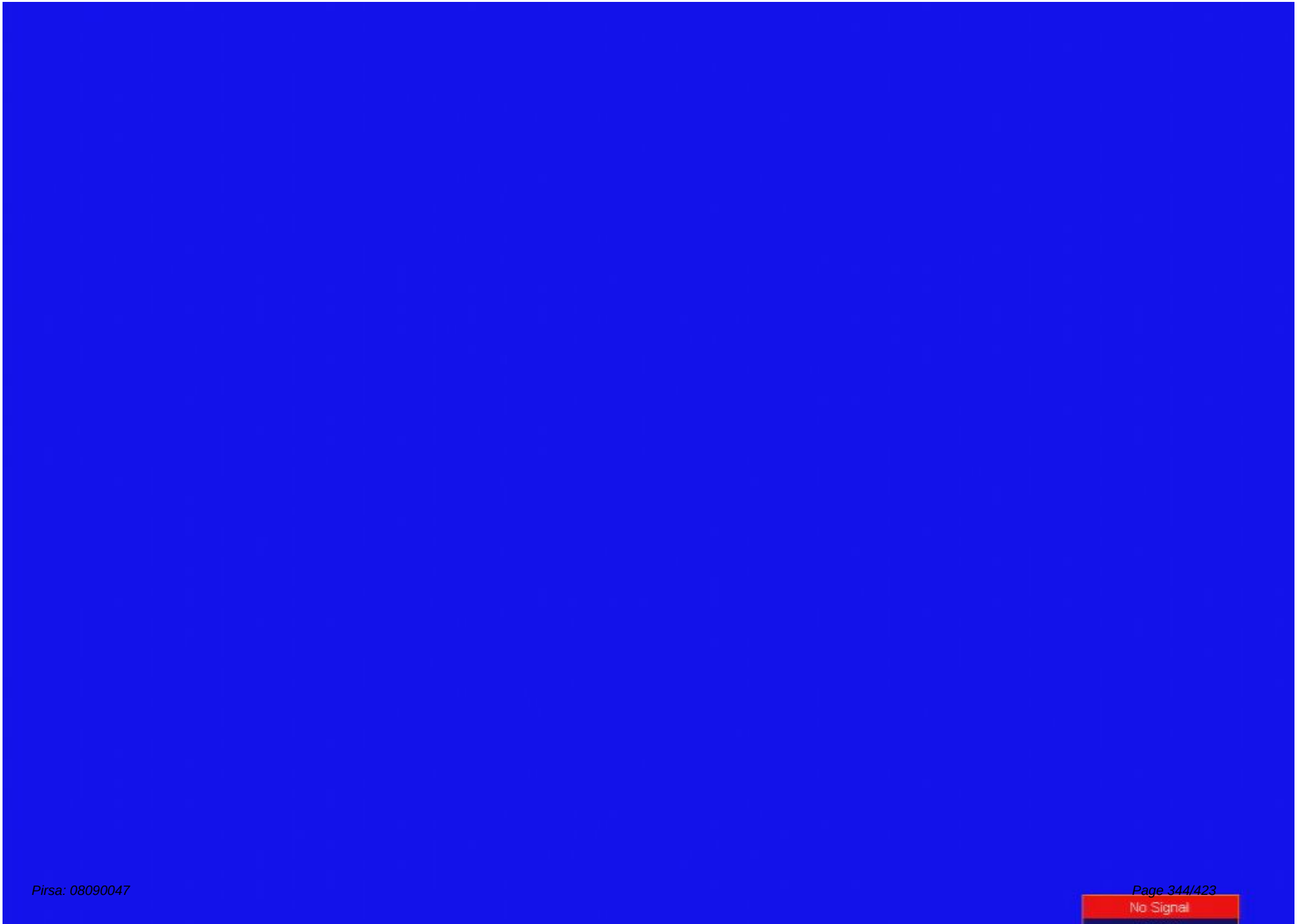

No Signal
VGA-1

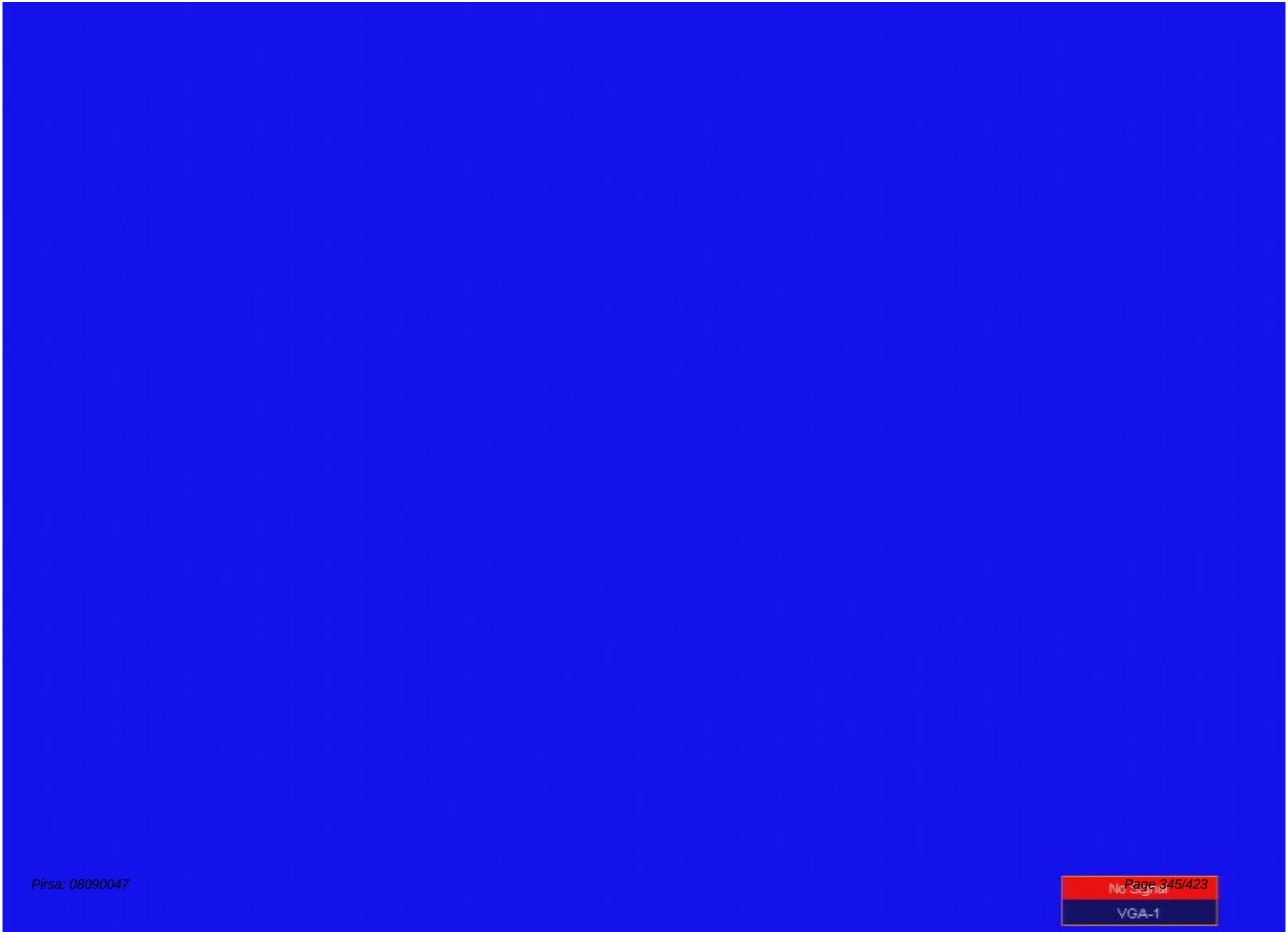

No Signal
VGA-1

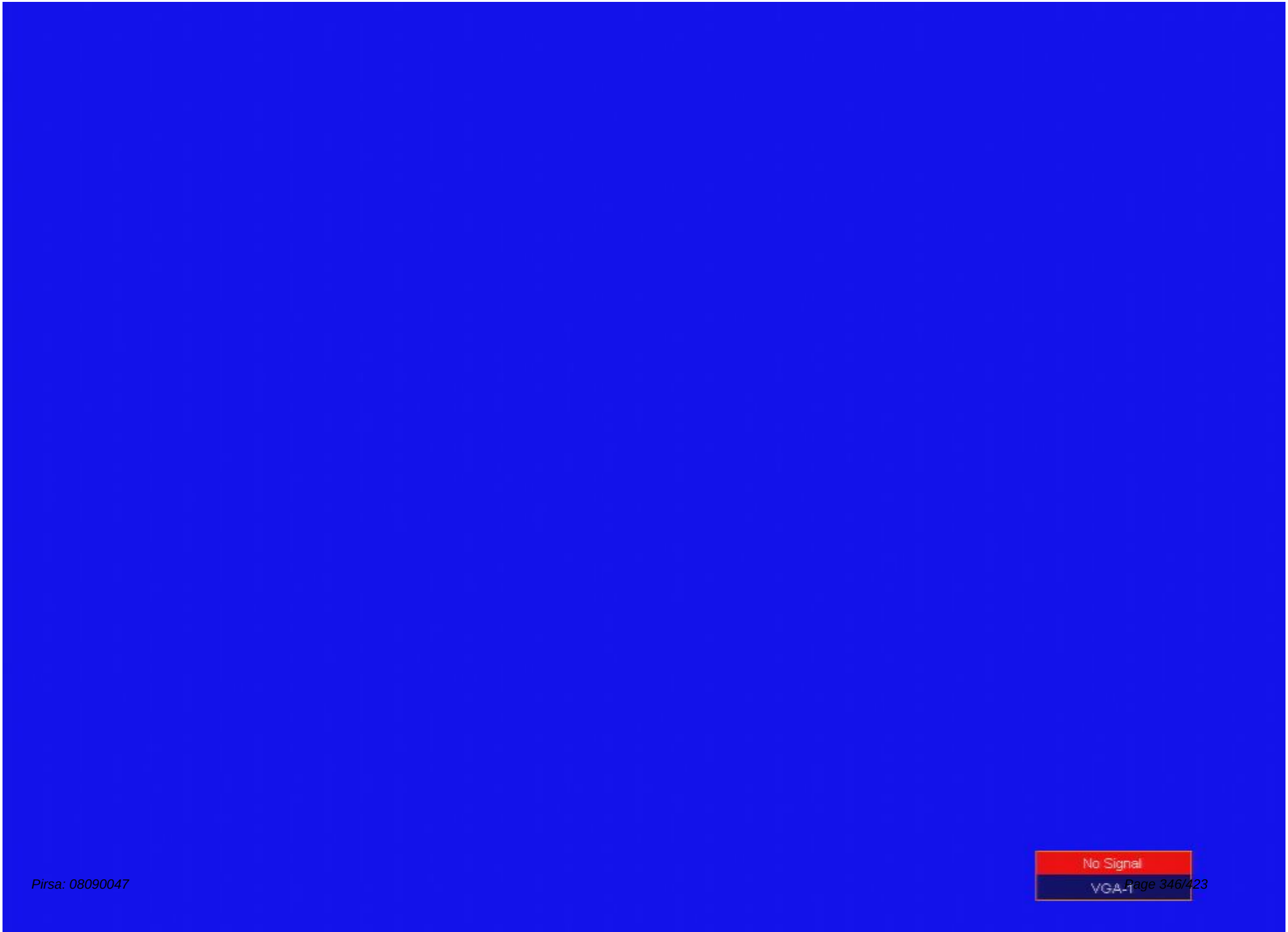

No Signal
VGA-1

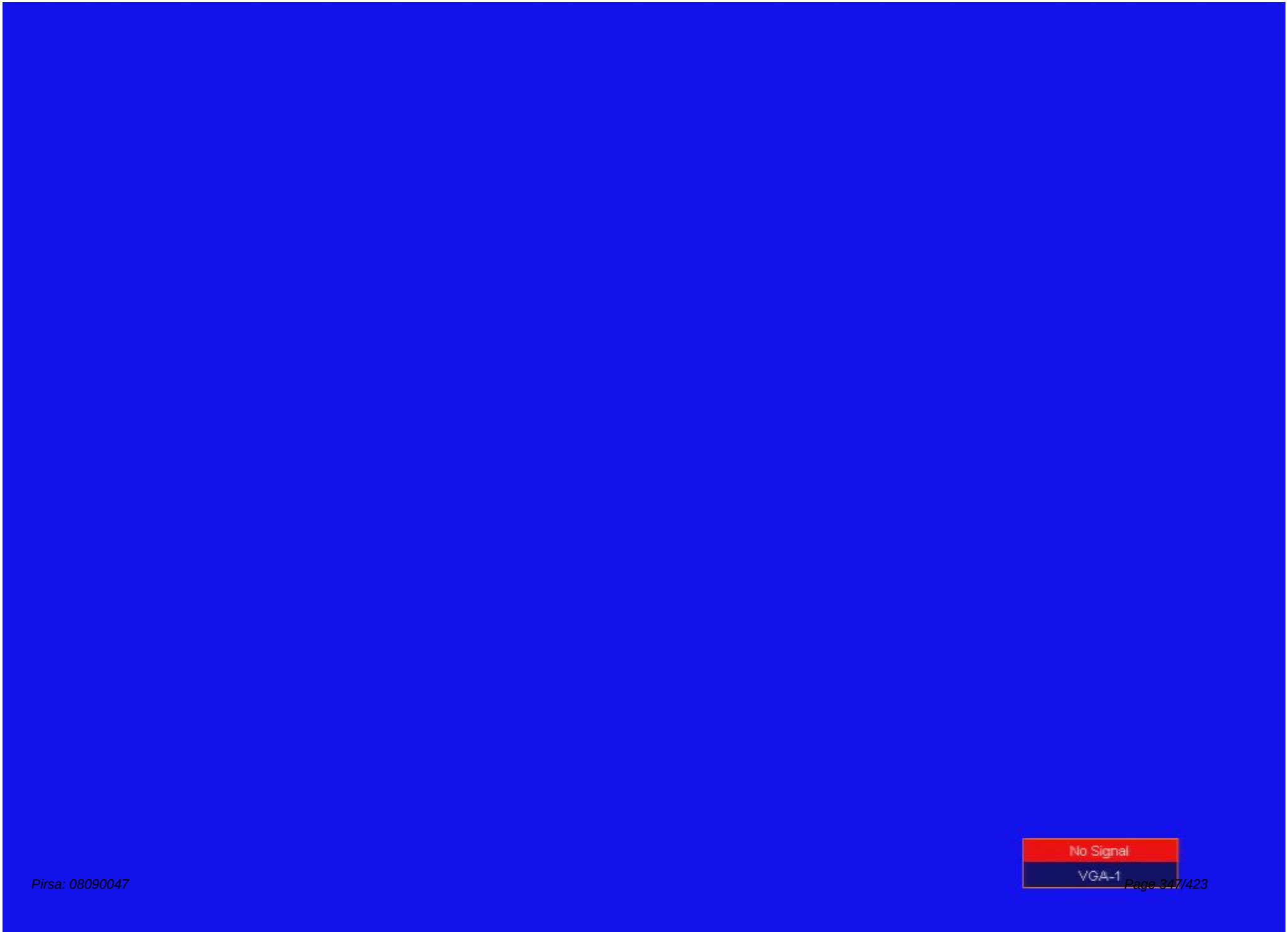

No Signal
VGA-1

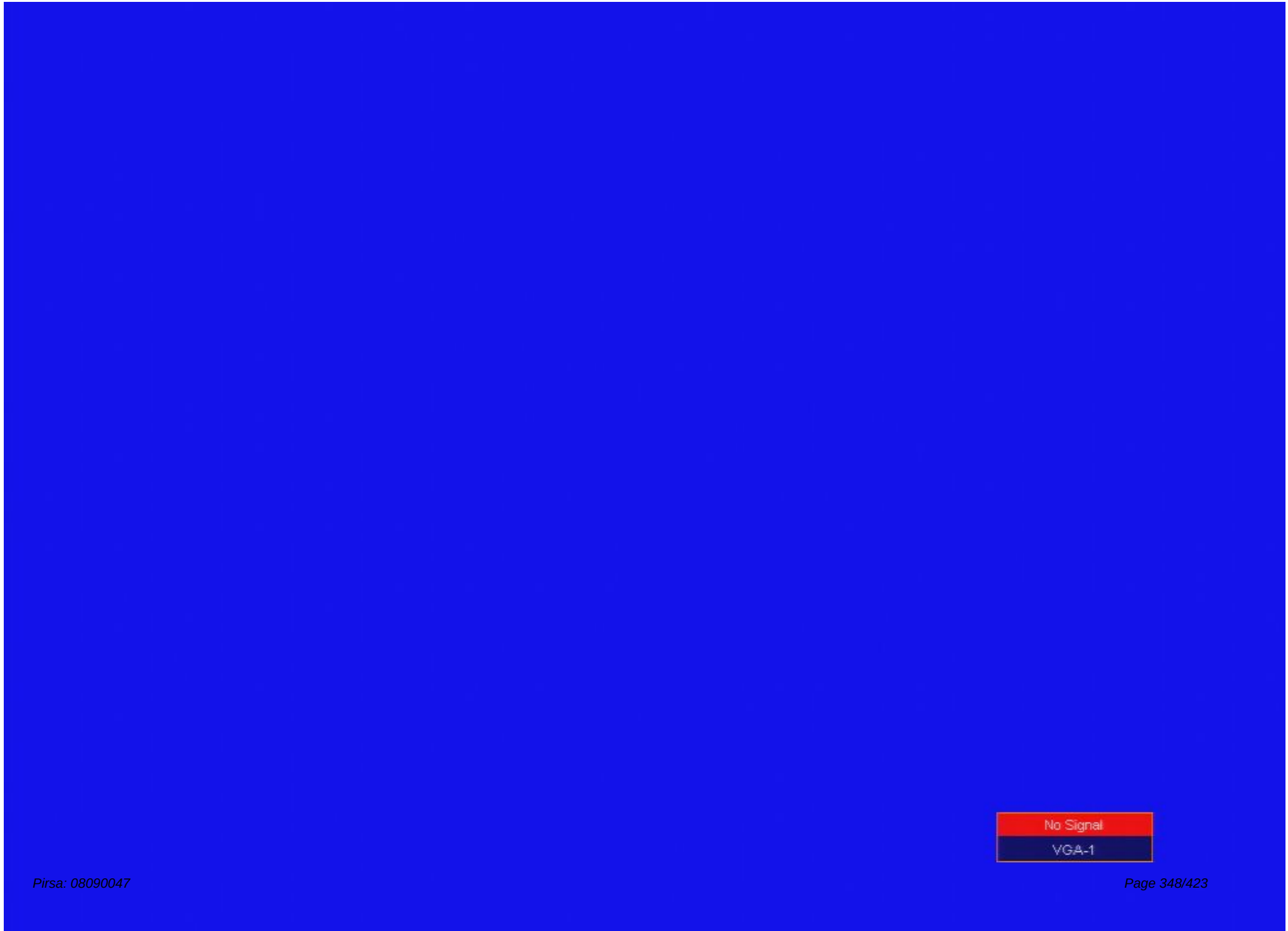
No Signal

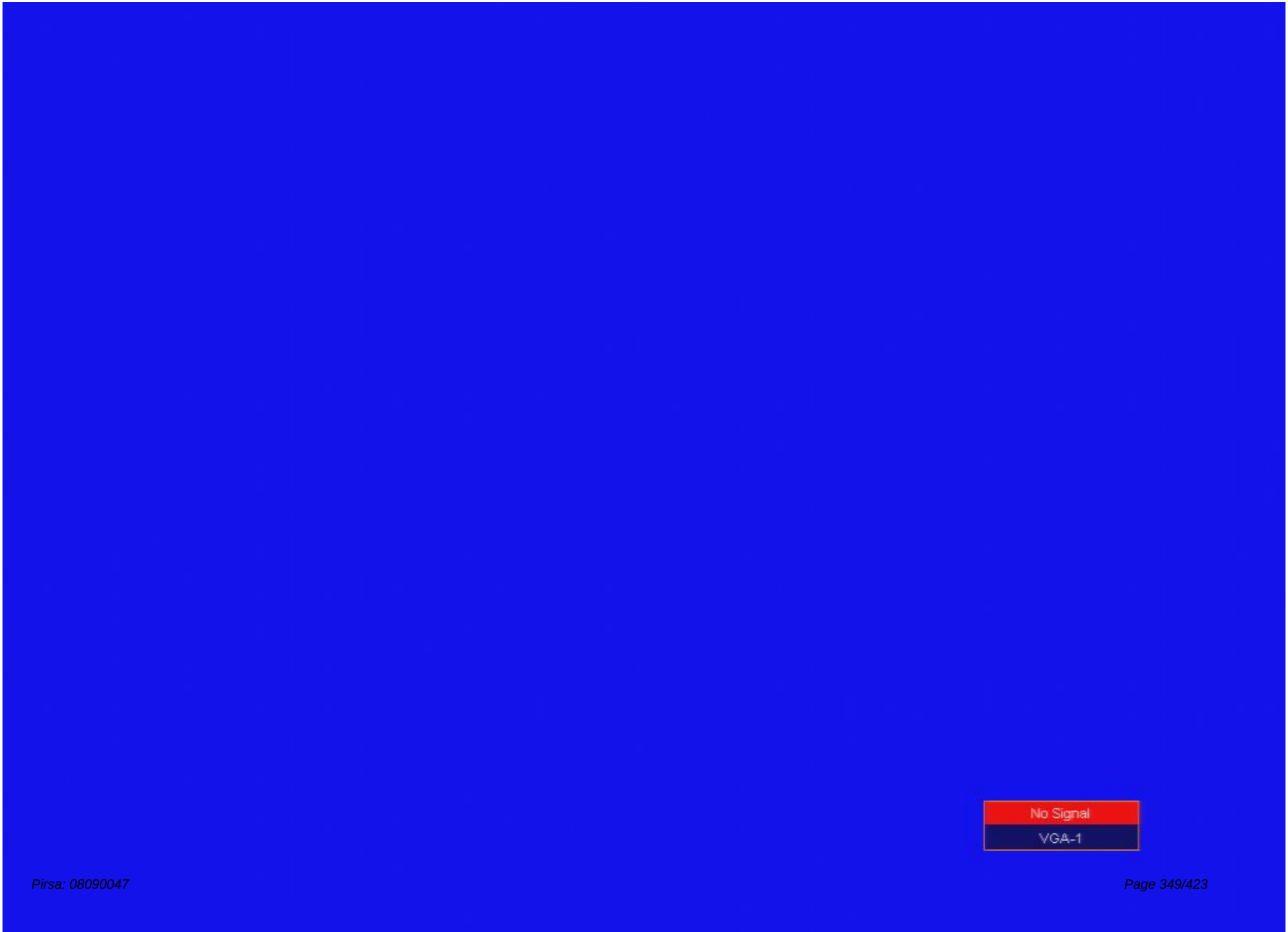

No Signal
VGA-1


No Signal
VGA-1

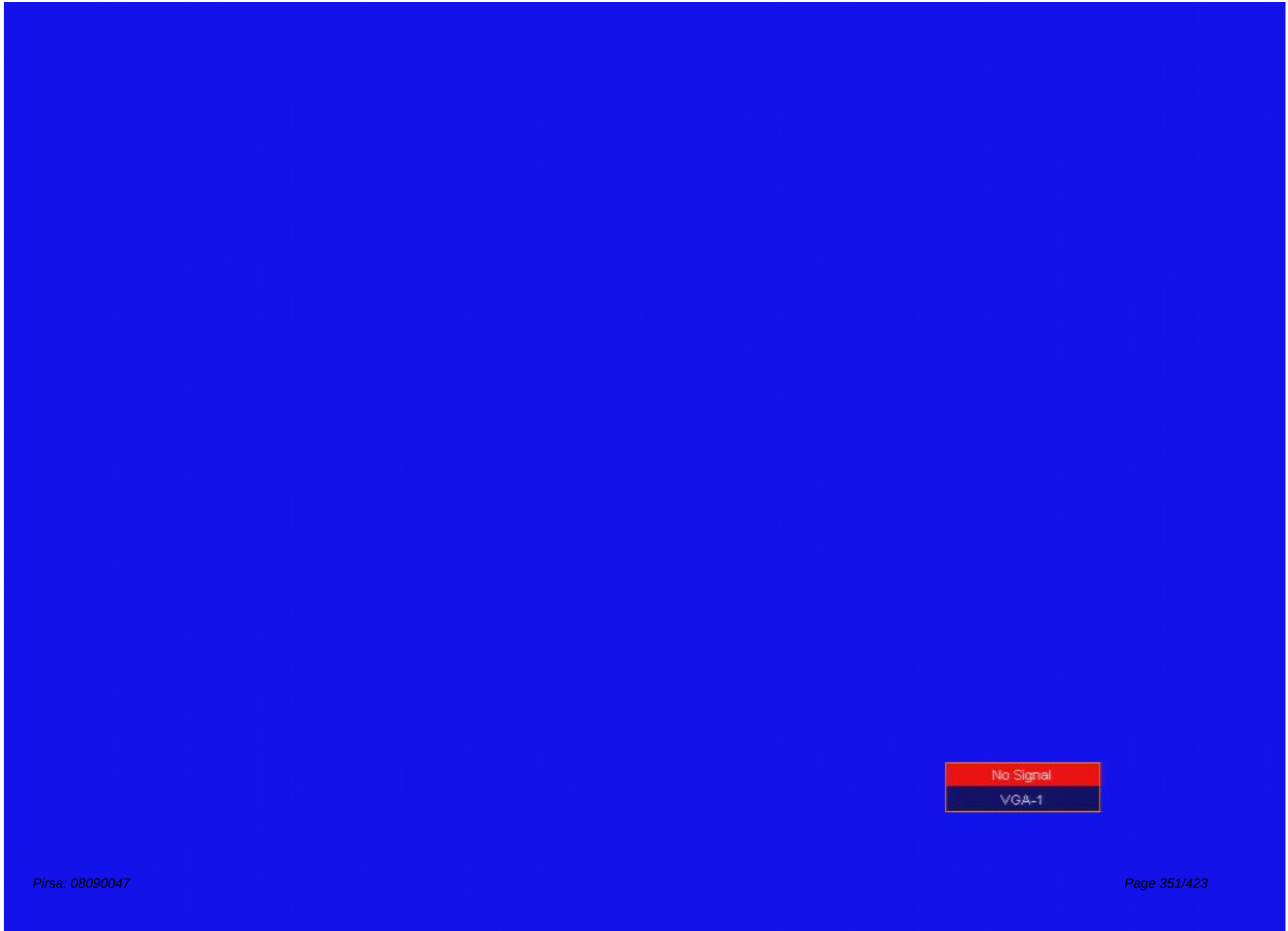

No Signal
VGA-1

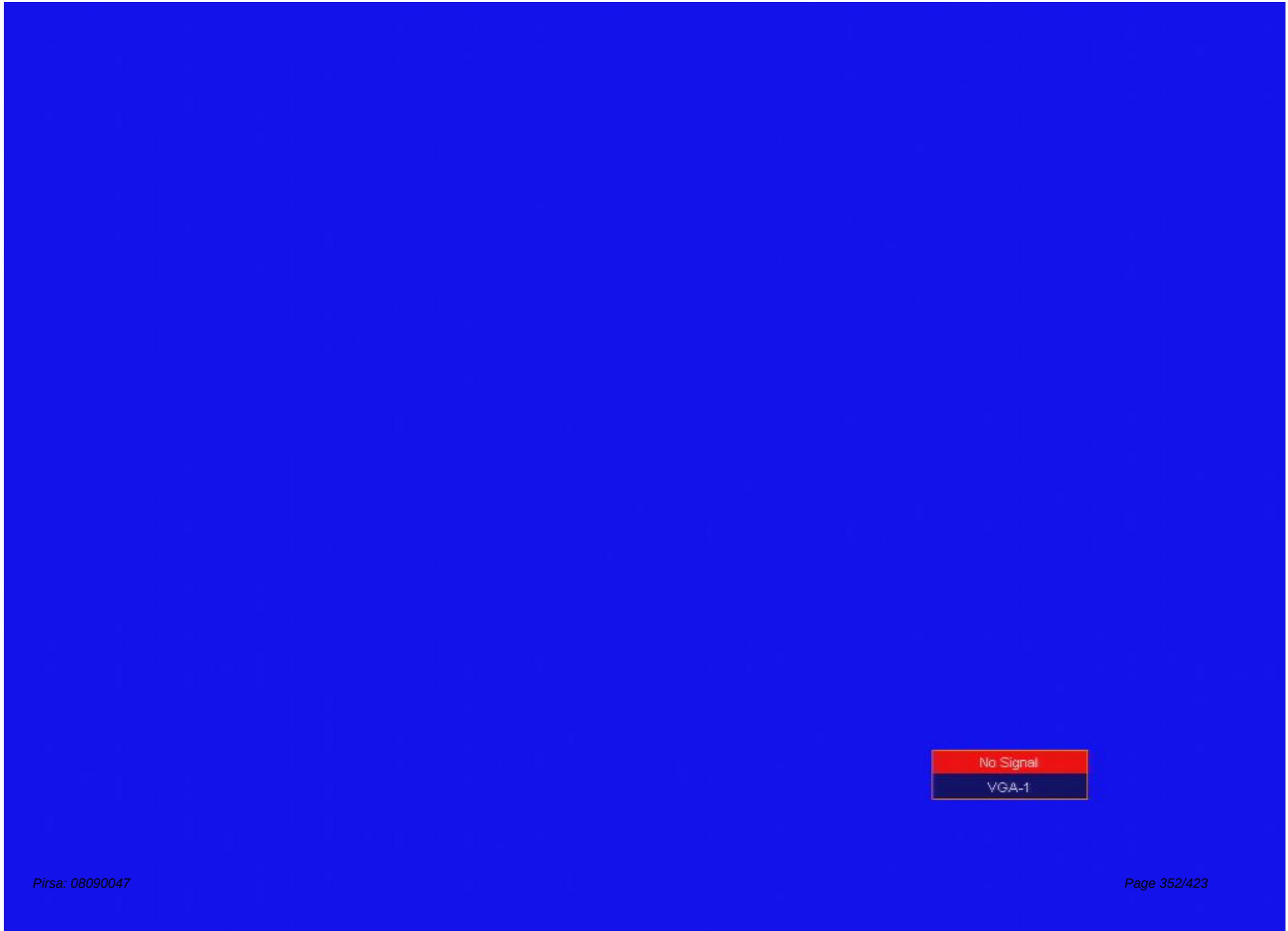

No Signal
VGA-1

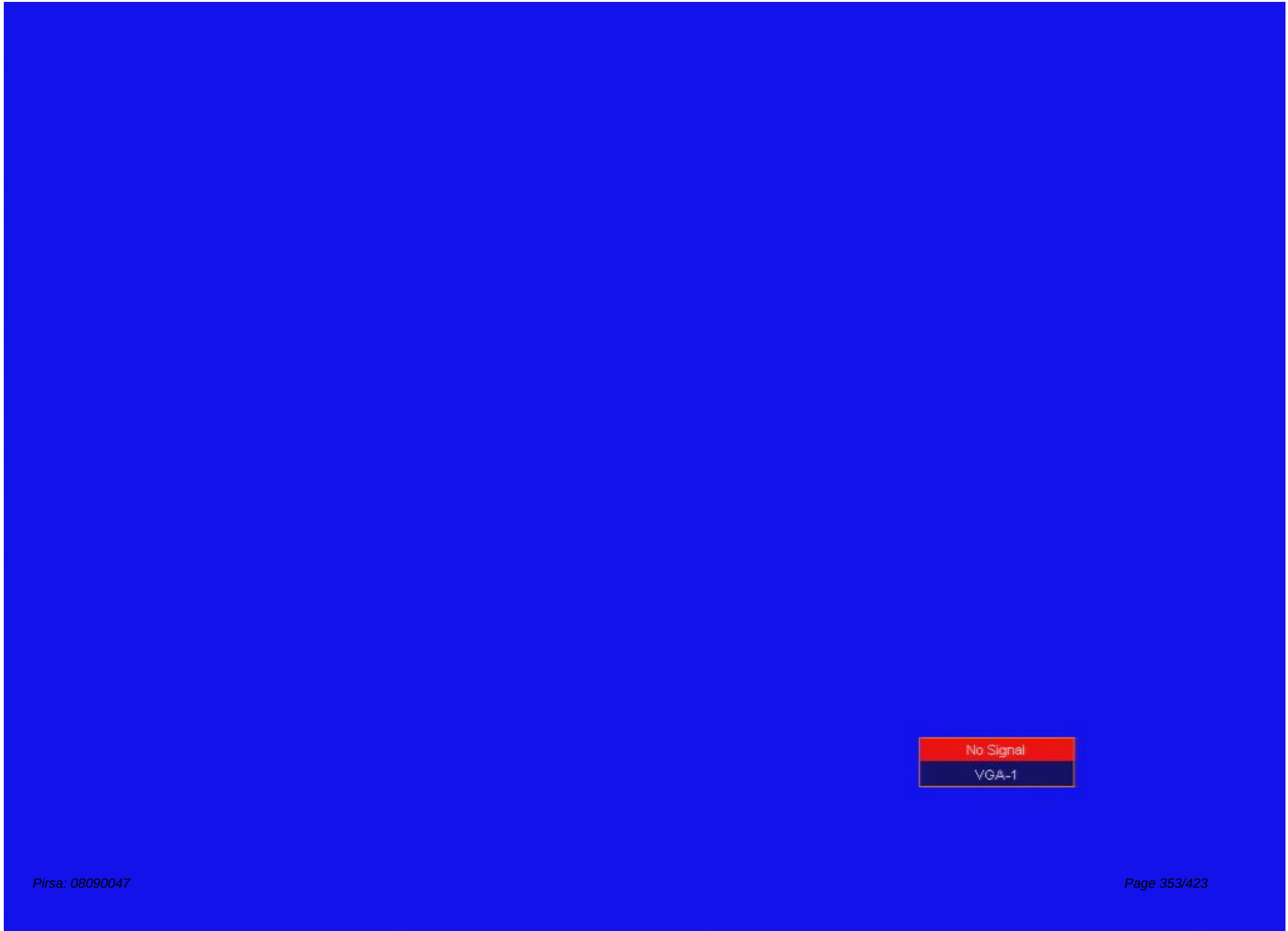

No Signal
VGA-1

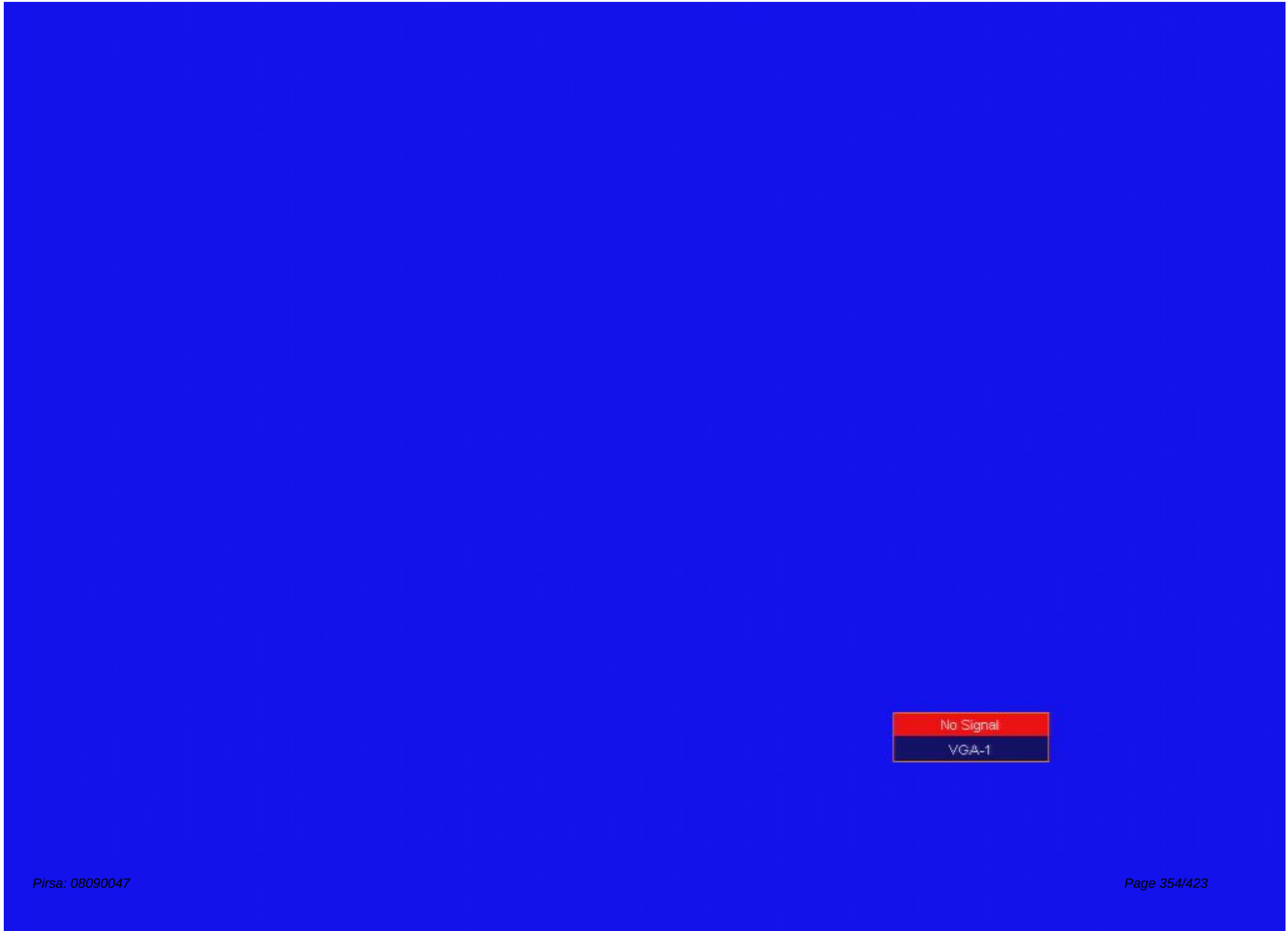

No Signal
VGA-1

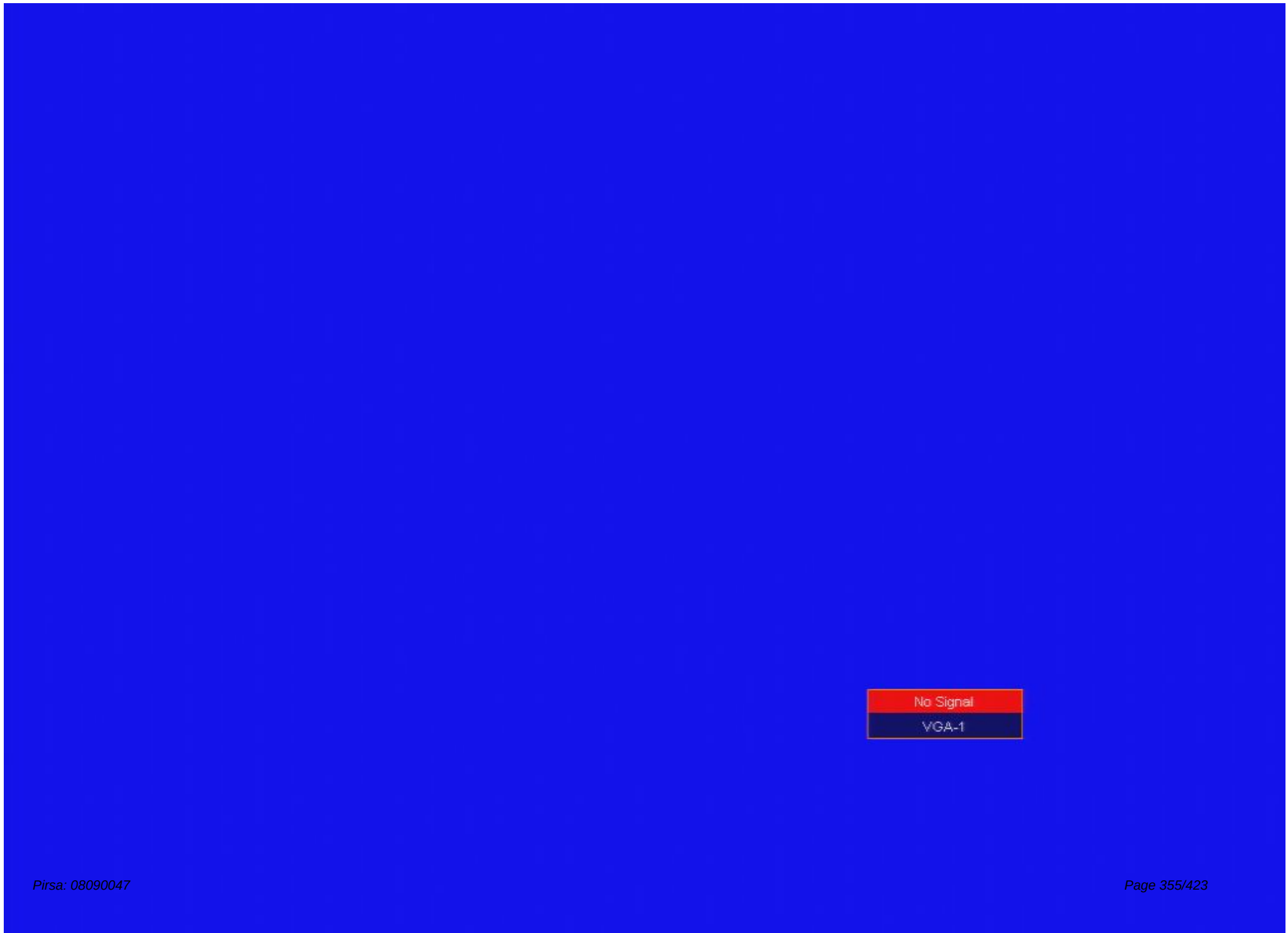

No Signal
VGA-1

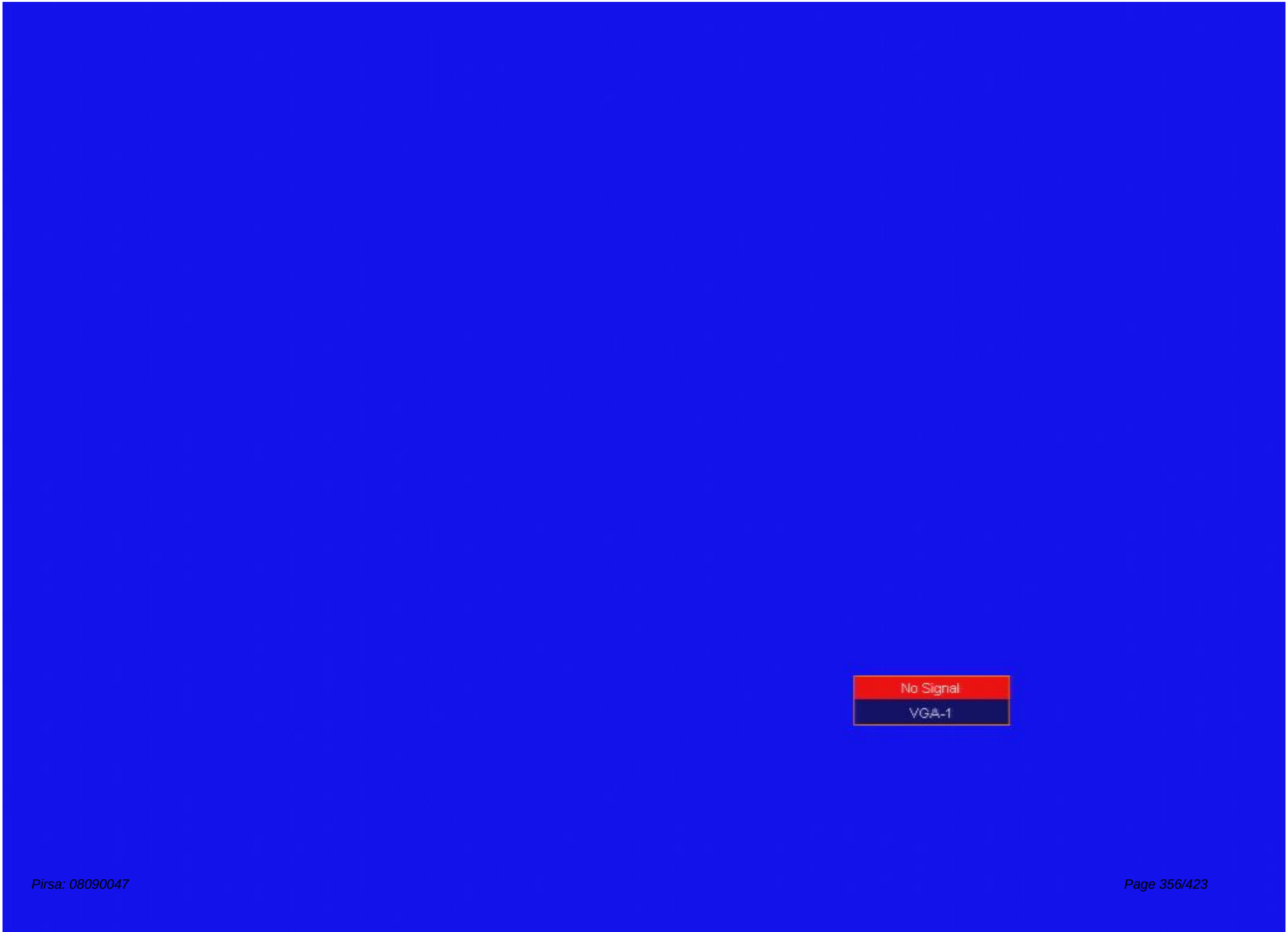

No Signal
VGA-1

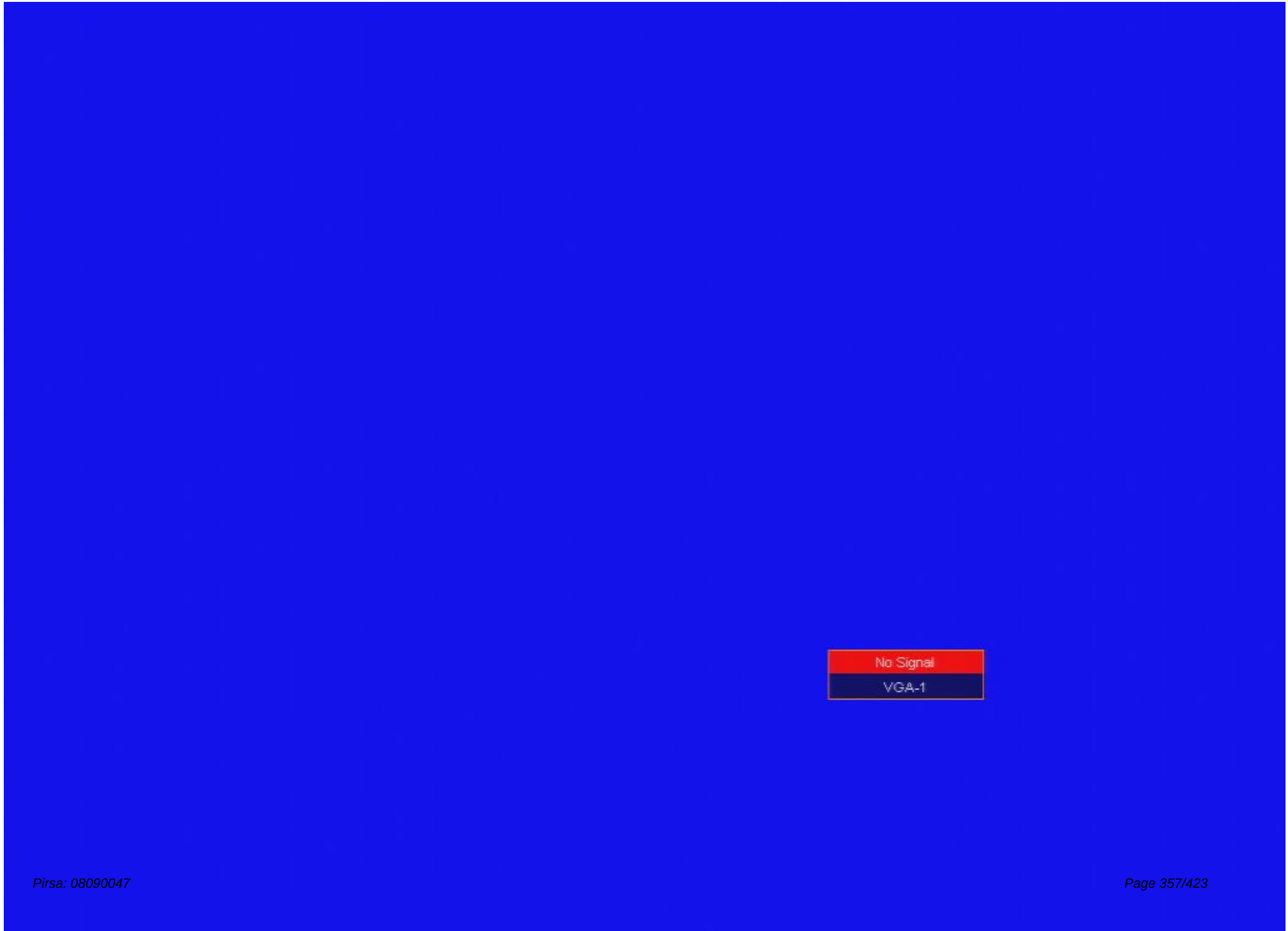

No Signal
VGA-1

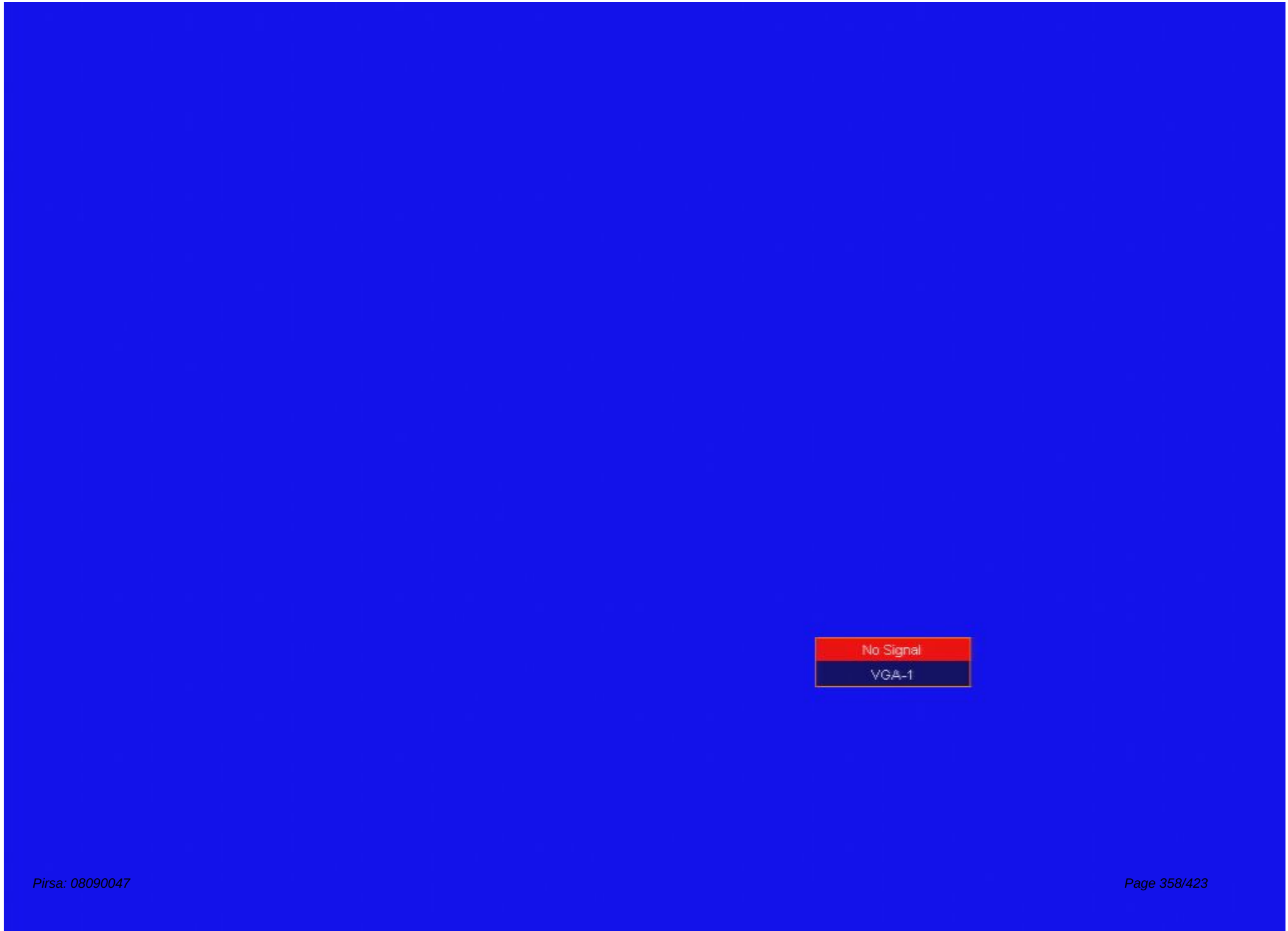

No Signal
VGA-1

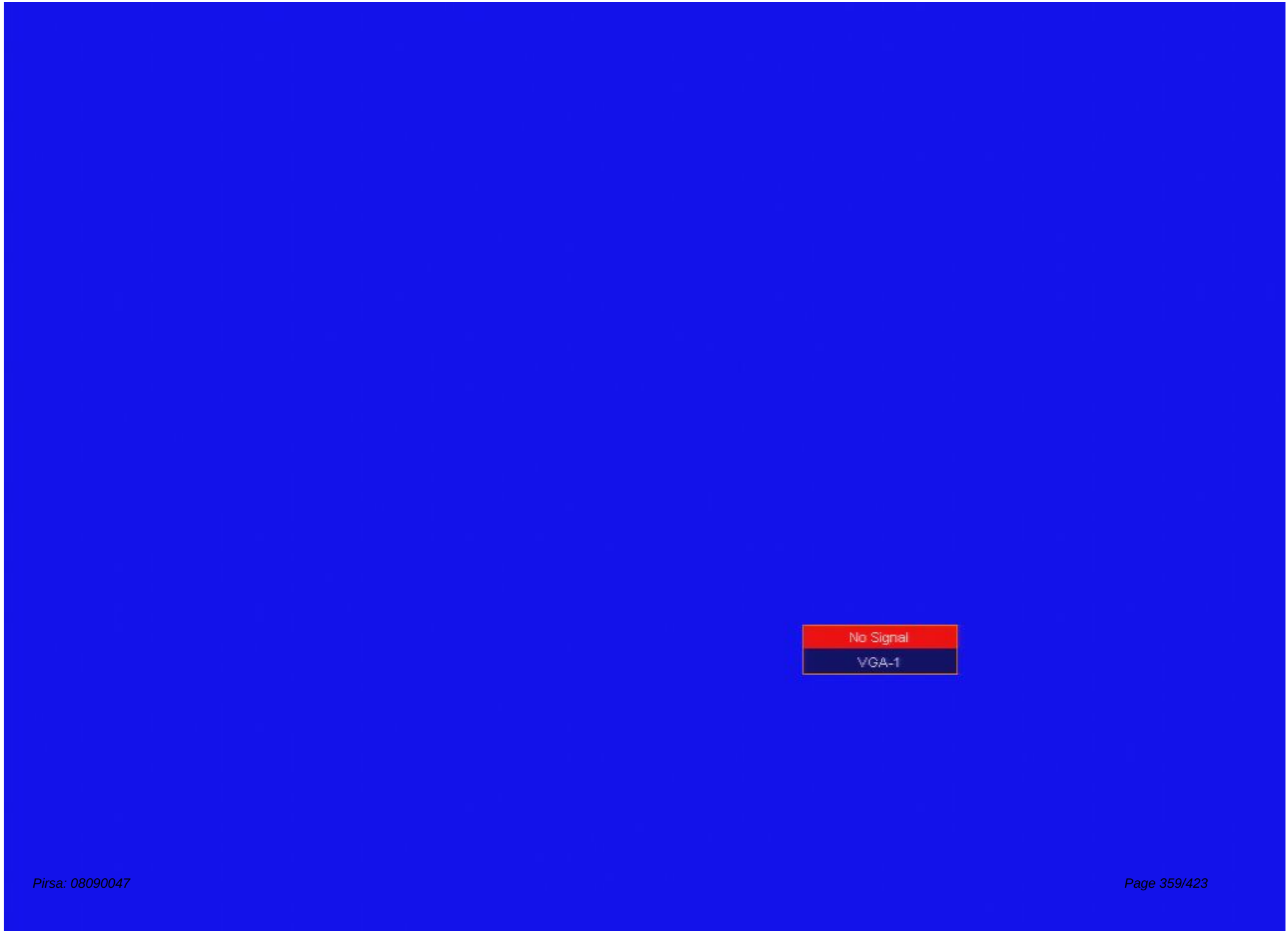

No Signal
VGA-1

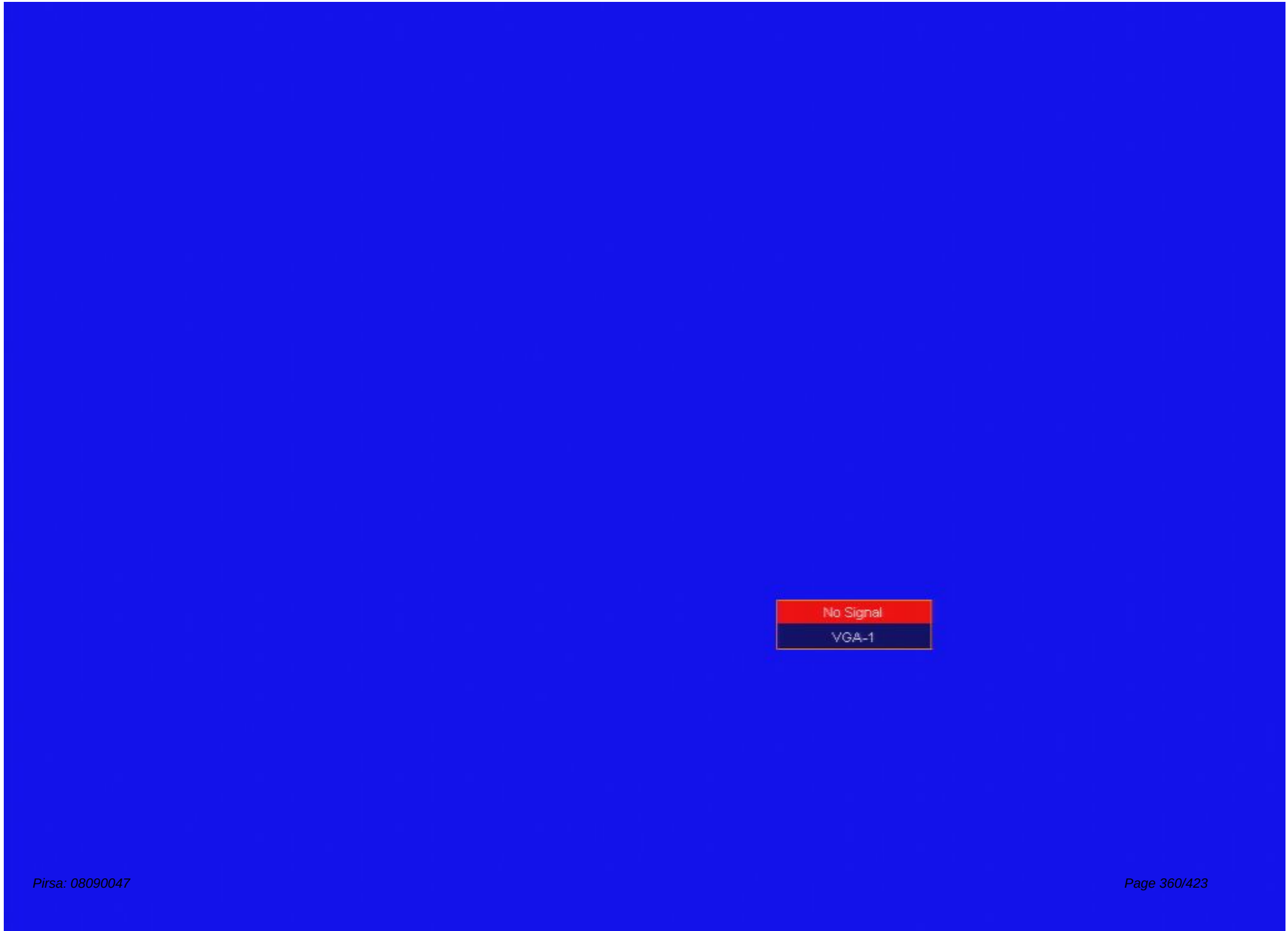

No Signal
VGA-1

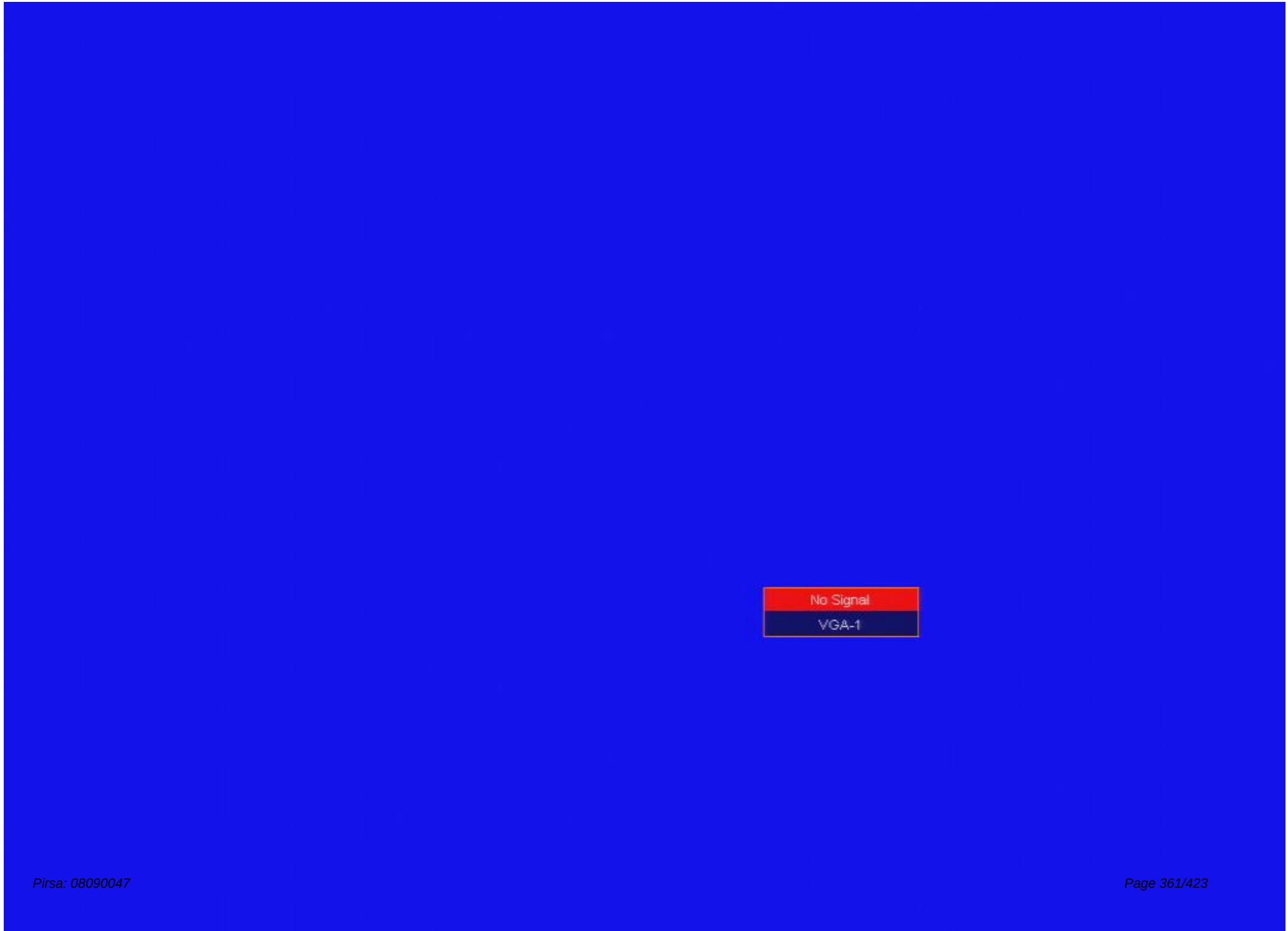

No Signal
VGA-1

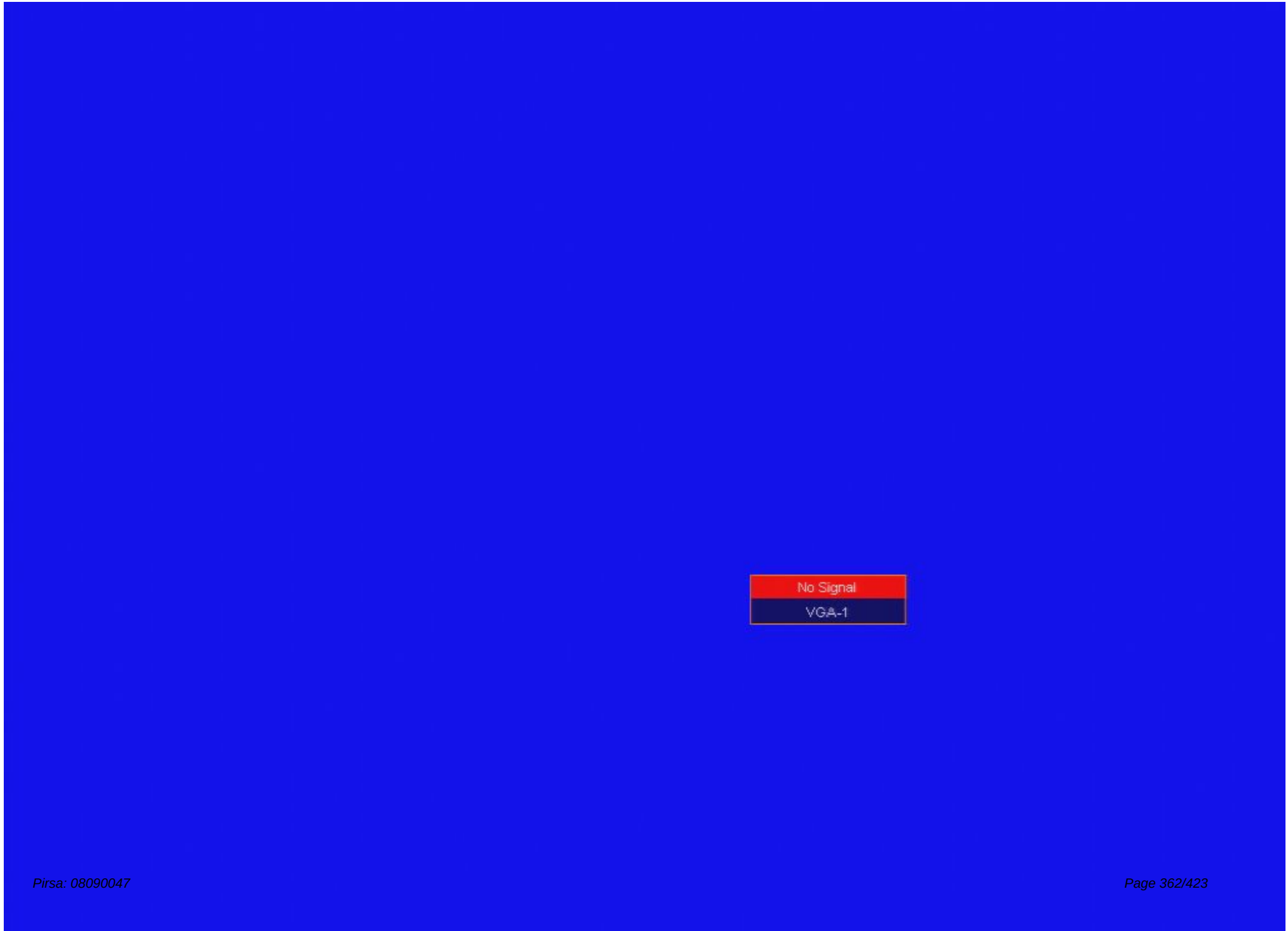

No Signal
VGA-1

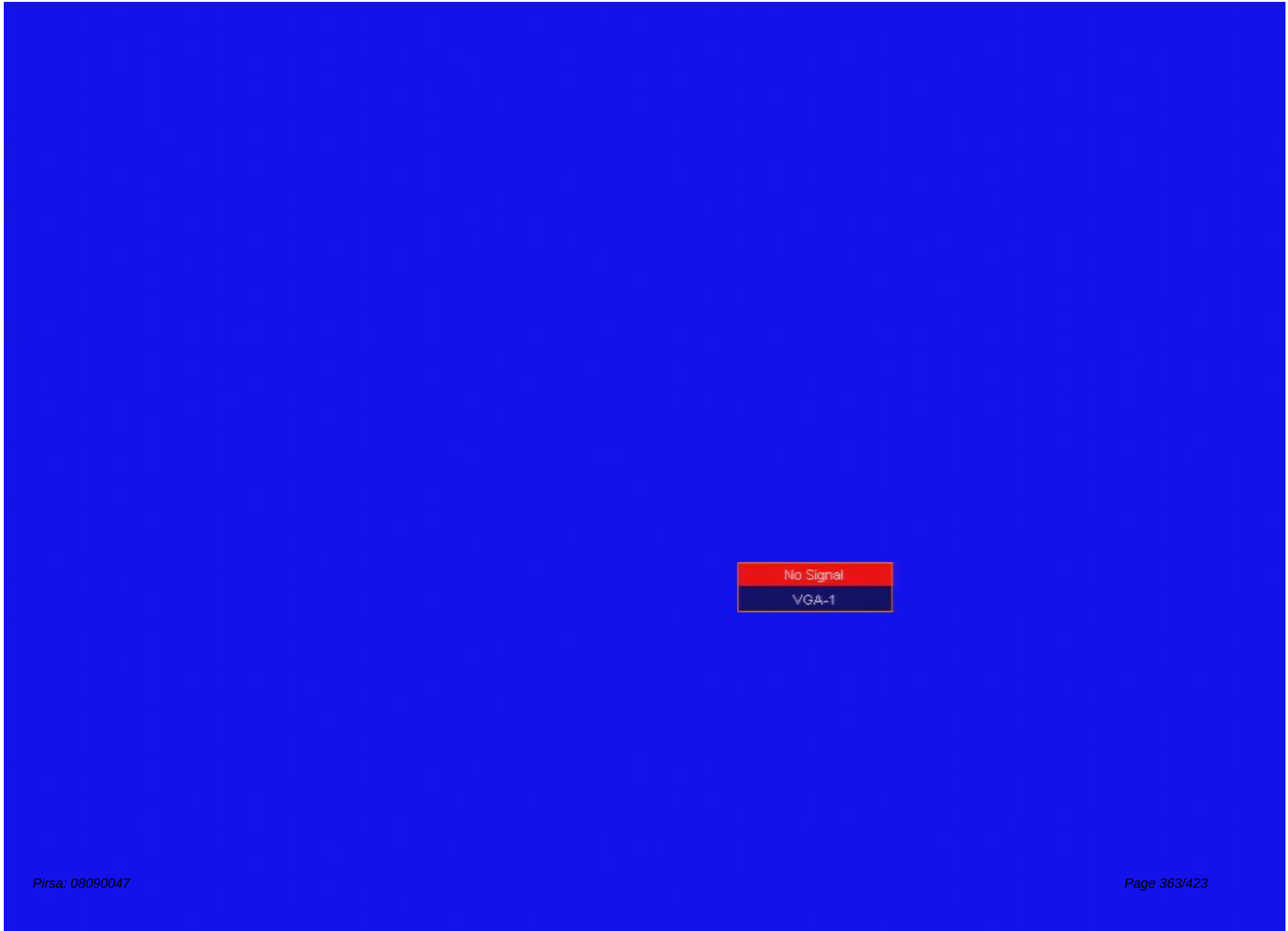

No Signal
VGA-1

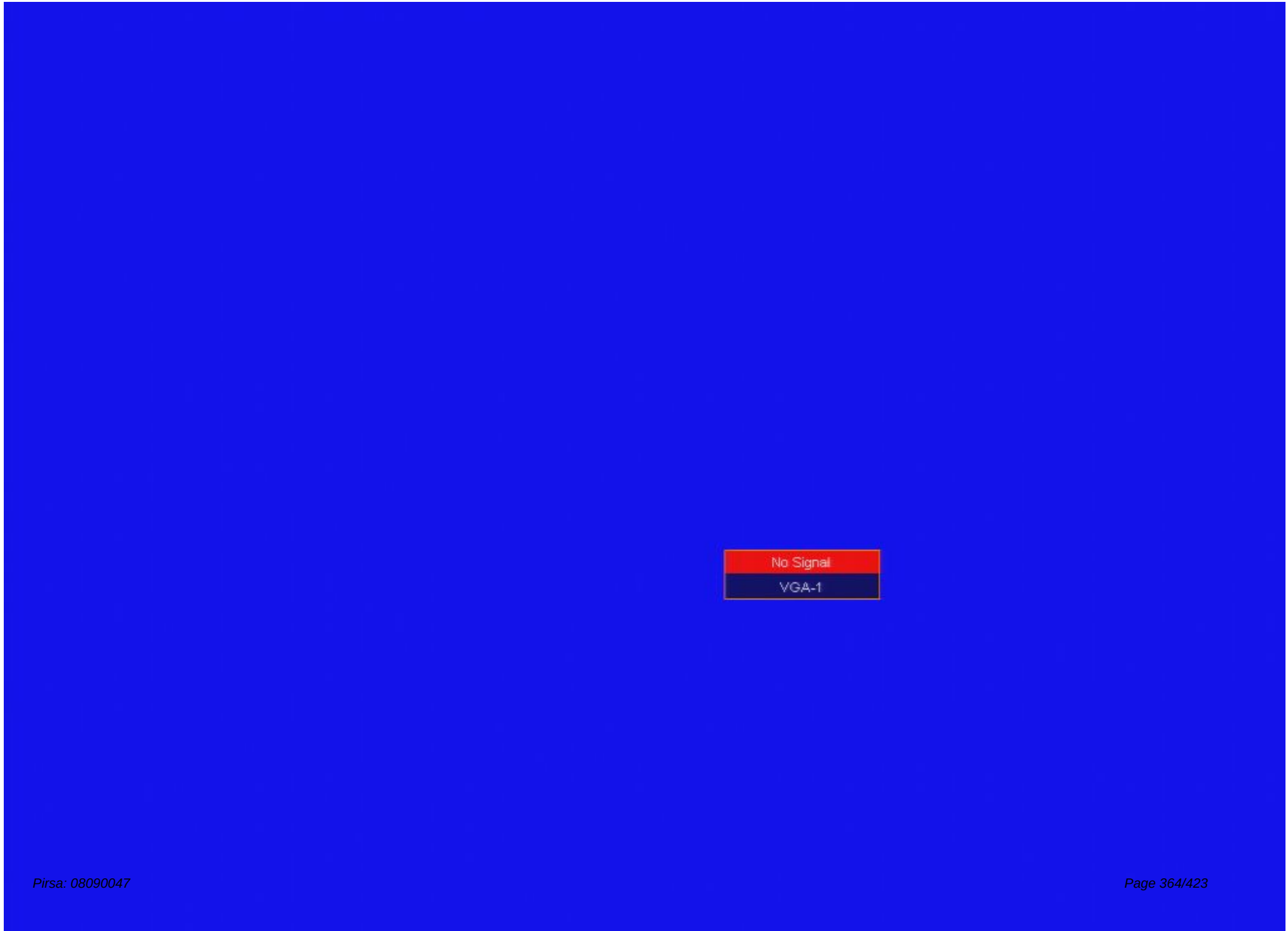

No Signal
VGA-1

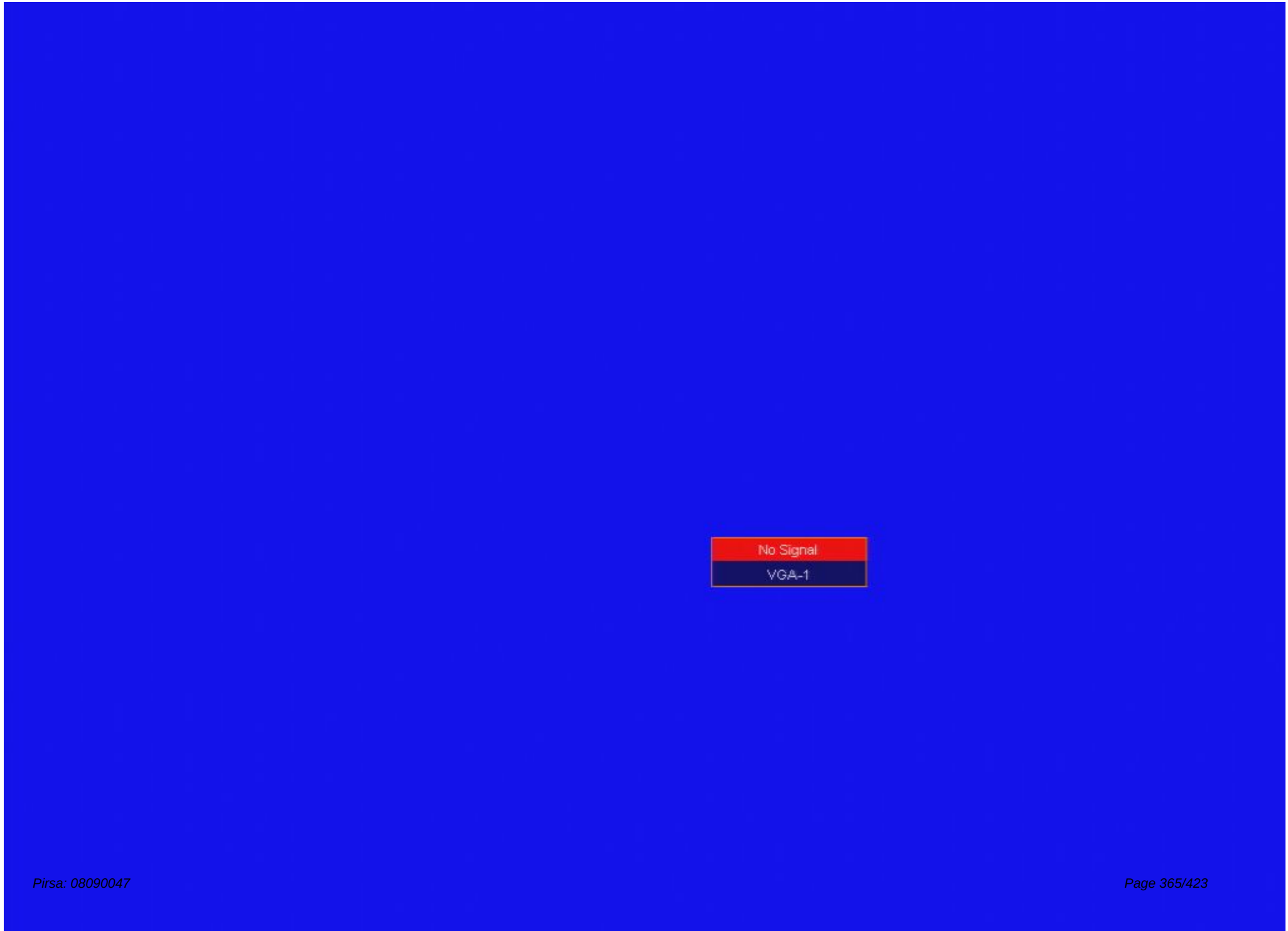

No Signal
VGA-1

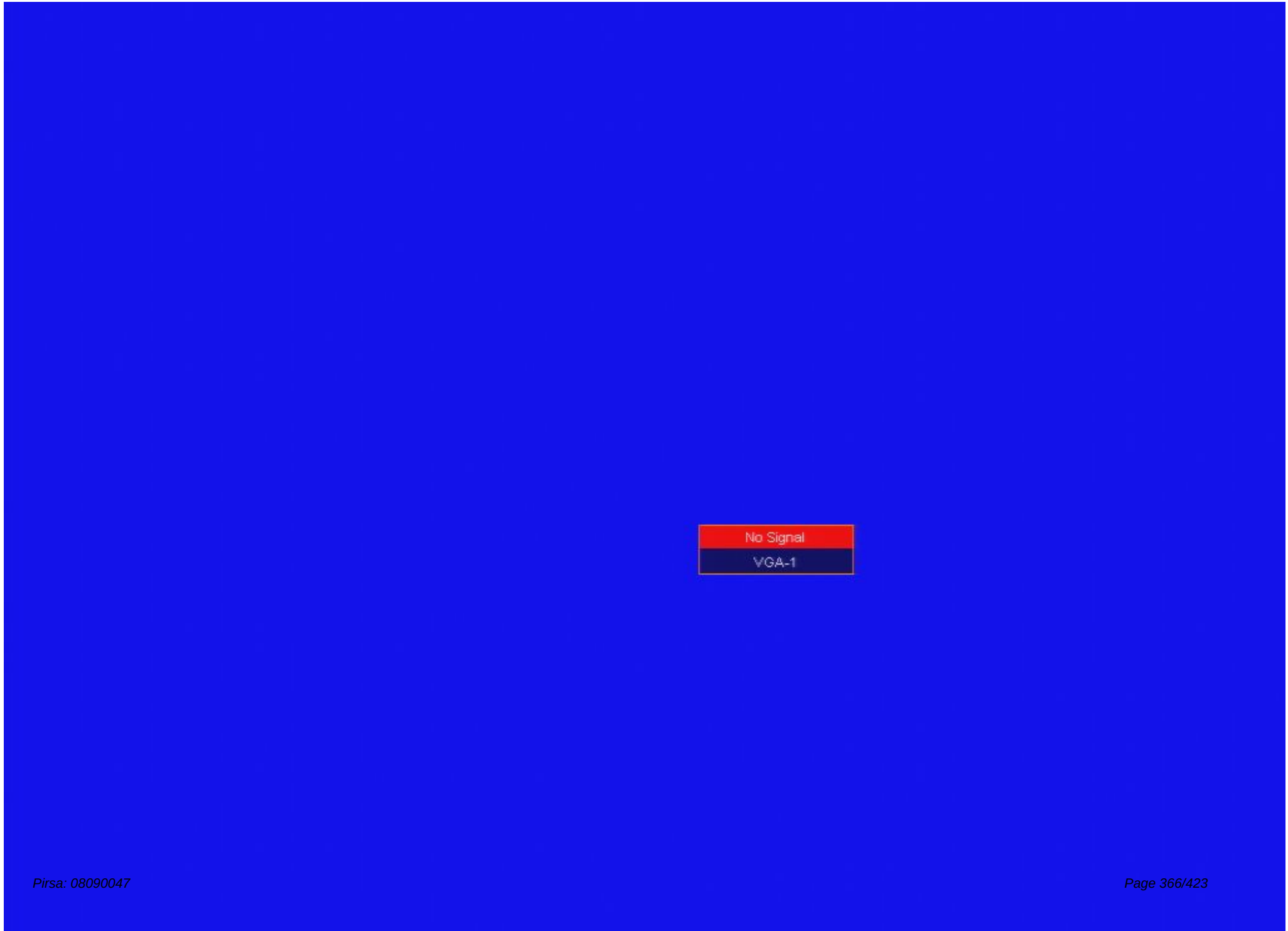

No Signal
VGA-1

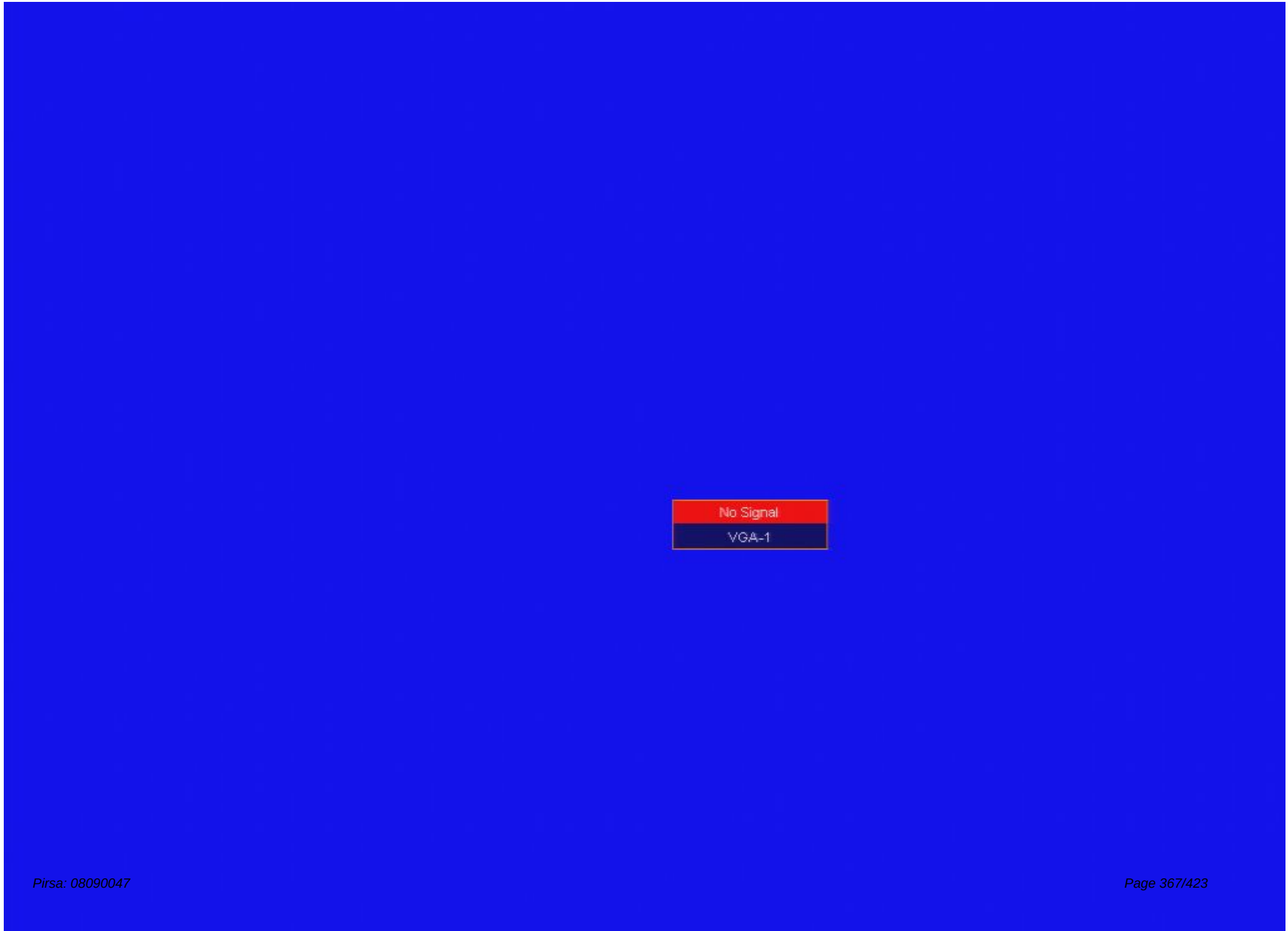

No Signal
VGA-1

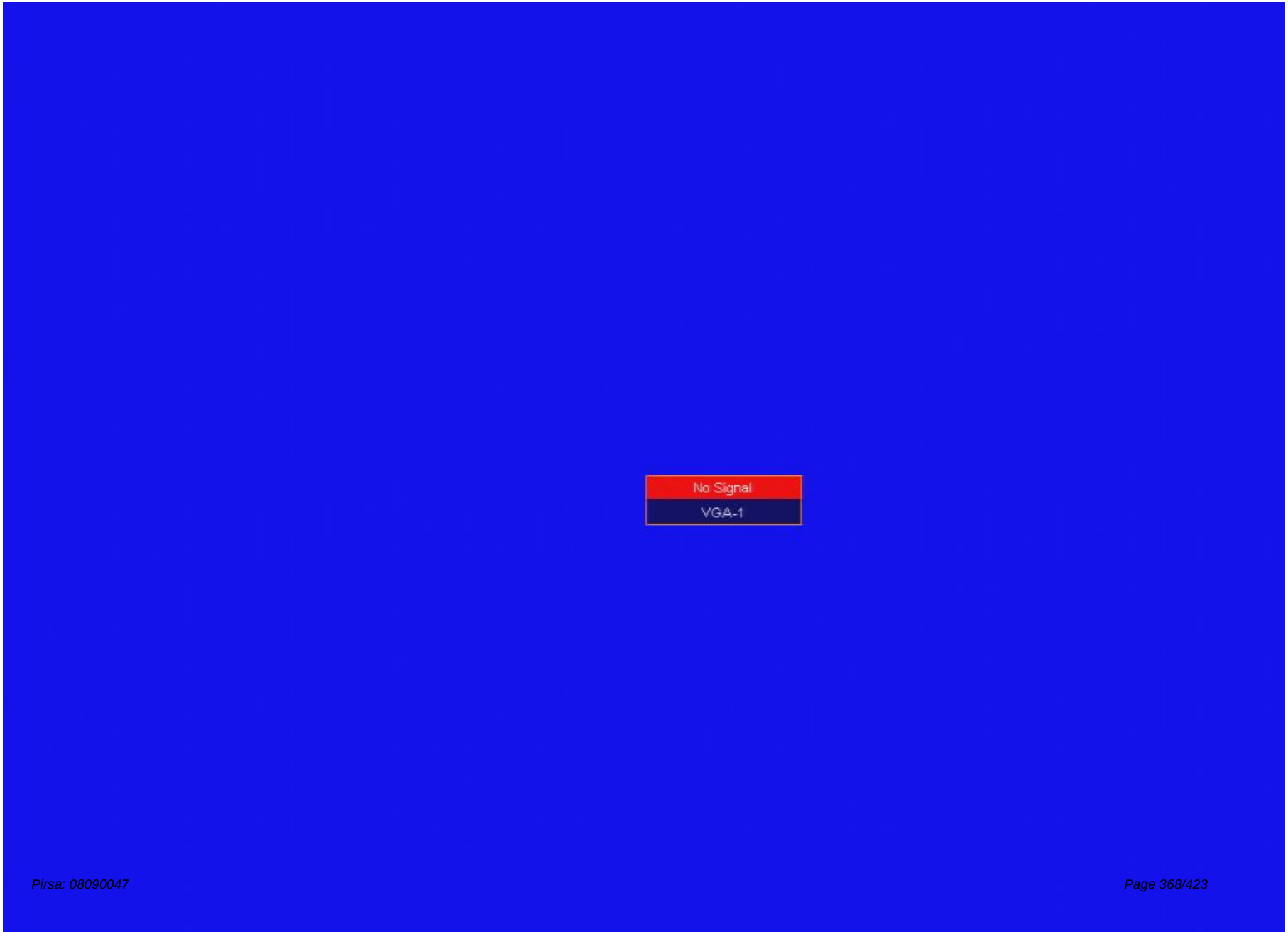

No Signal
VGA-1

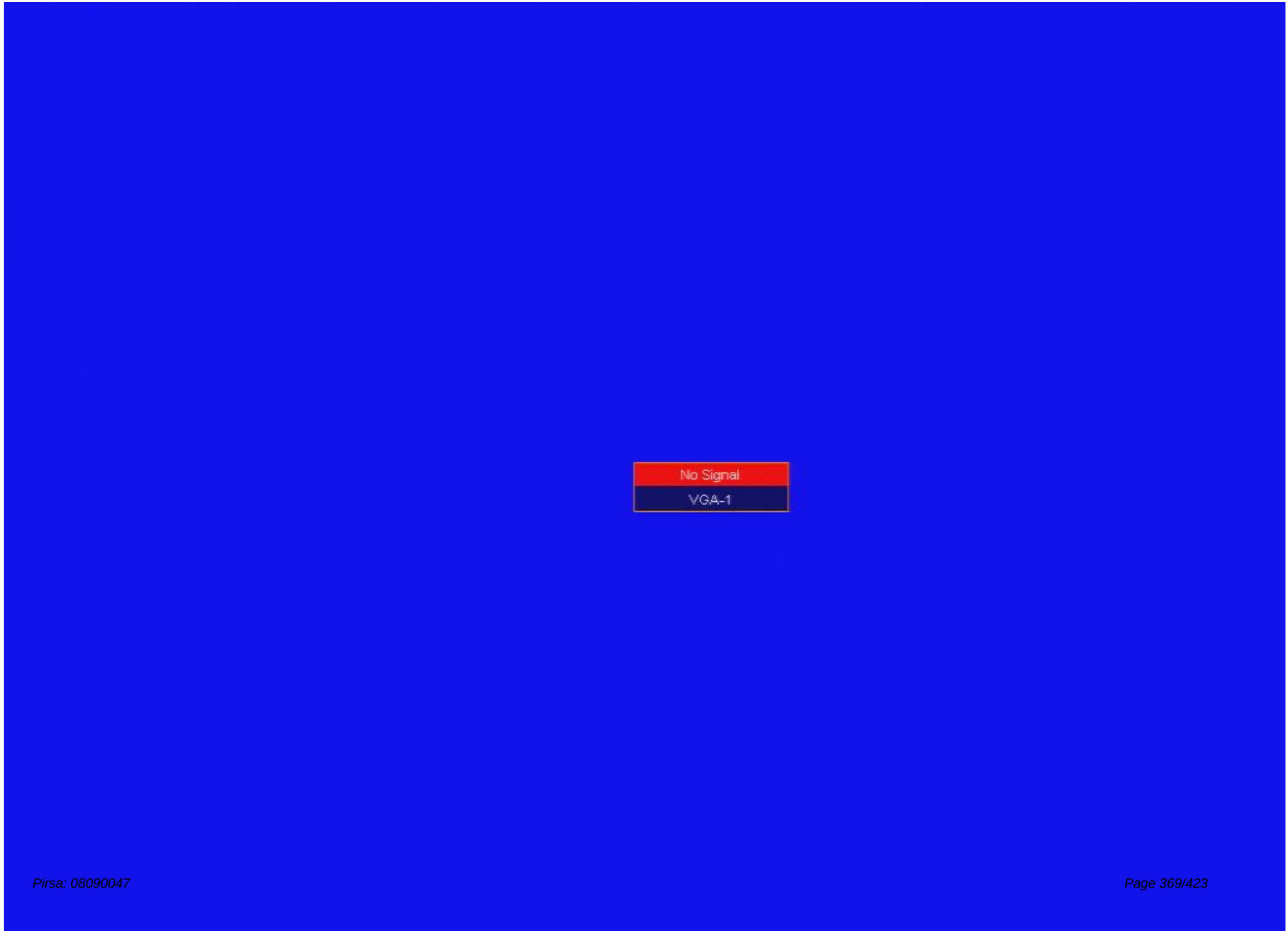

No Signal
VGA-1

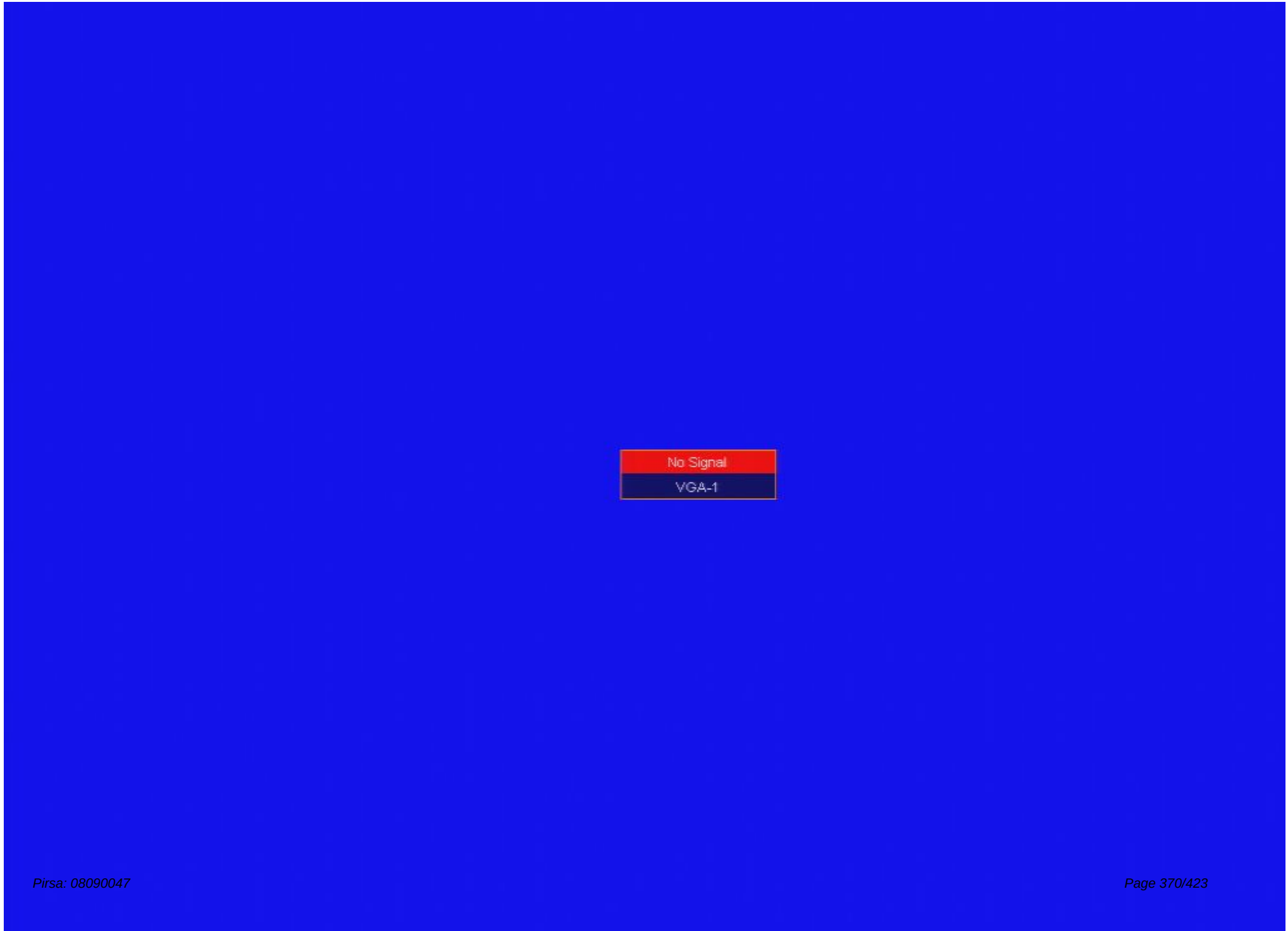

No Signal
VGA-1

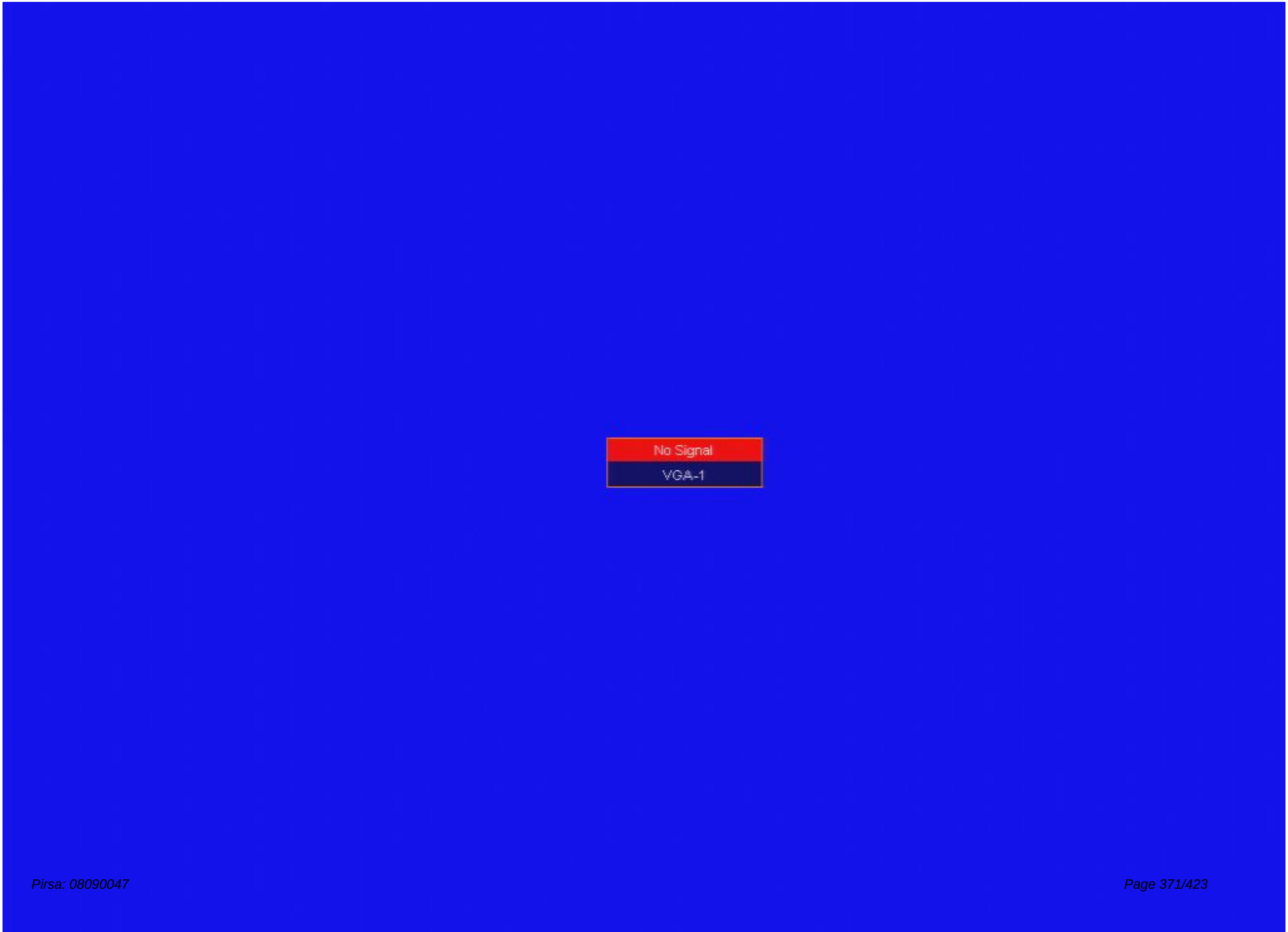

No Signal
VGA-1

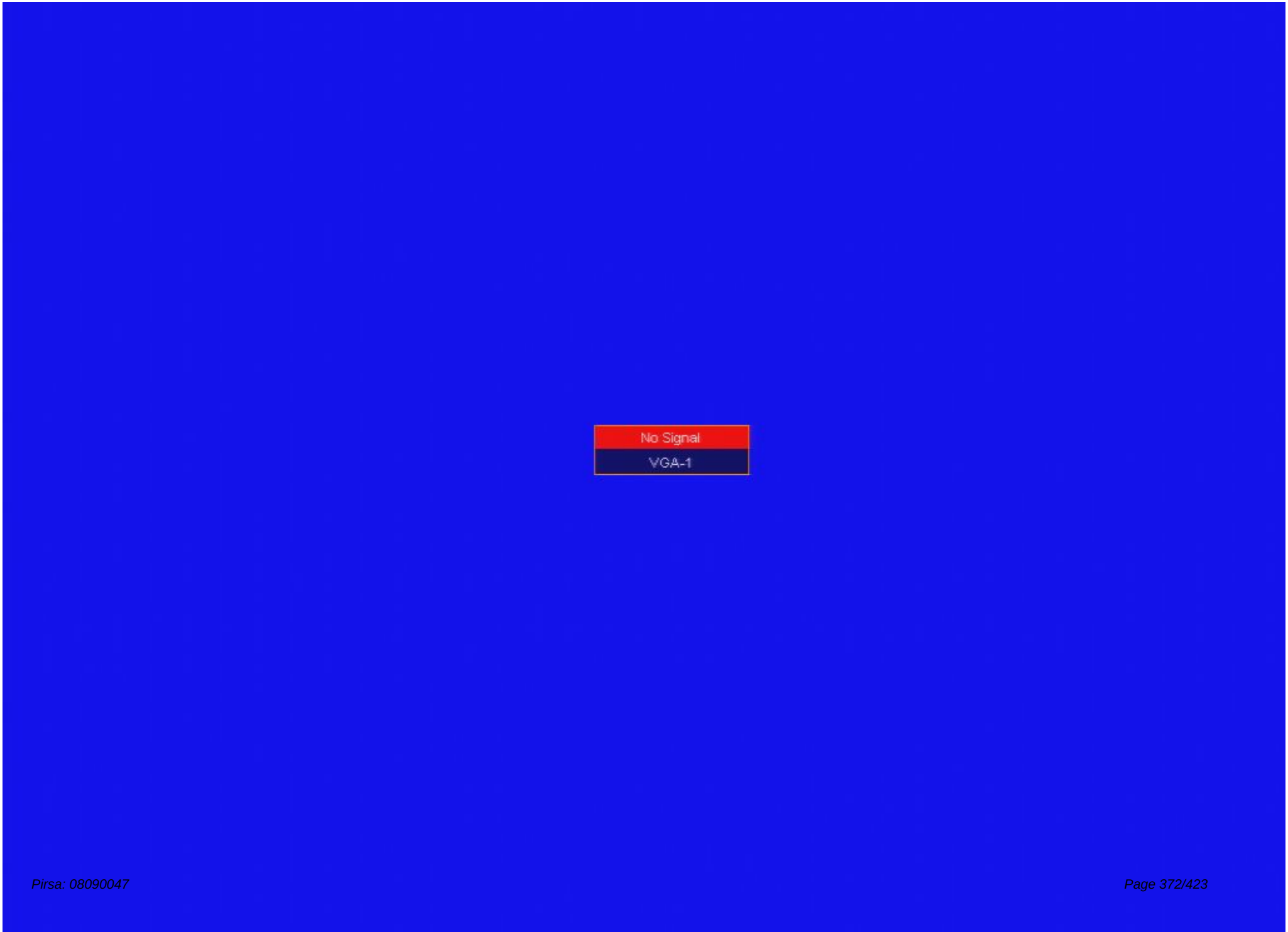

No Signal
VGA-1

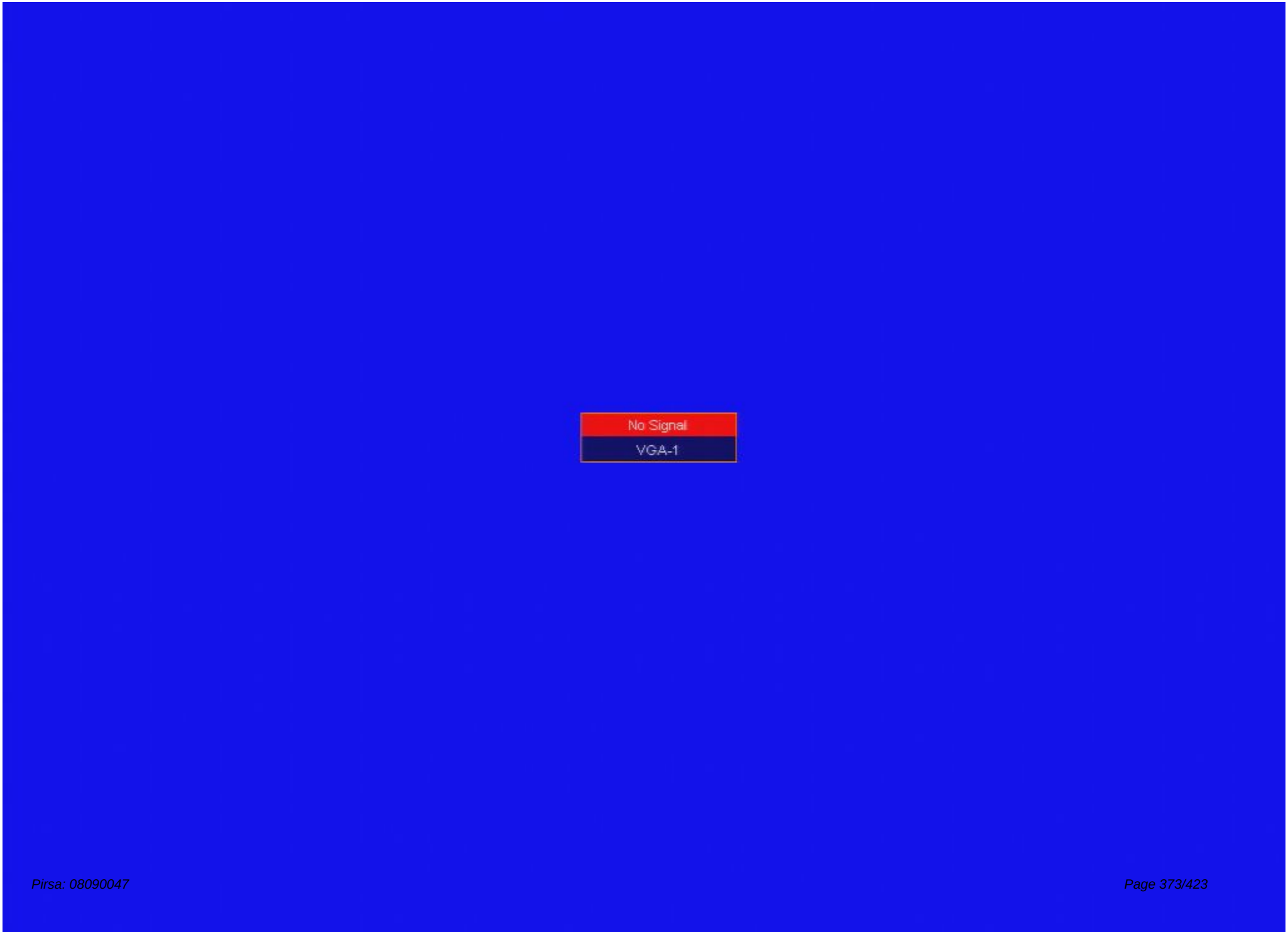

No Signal
VGA-1

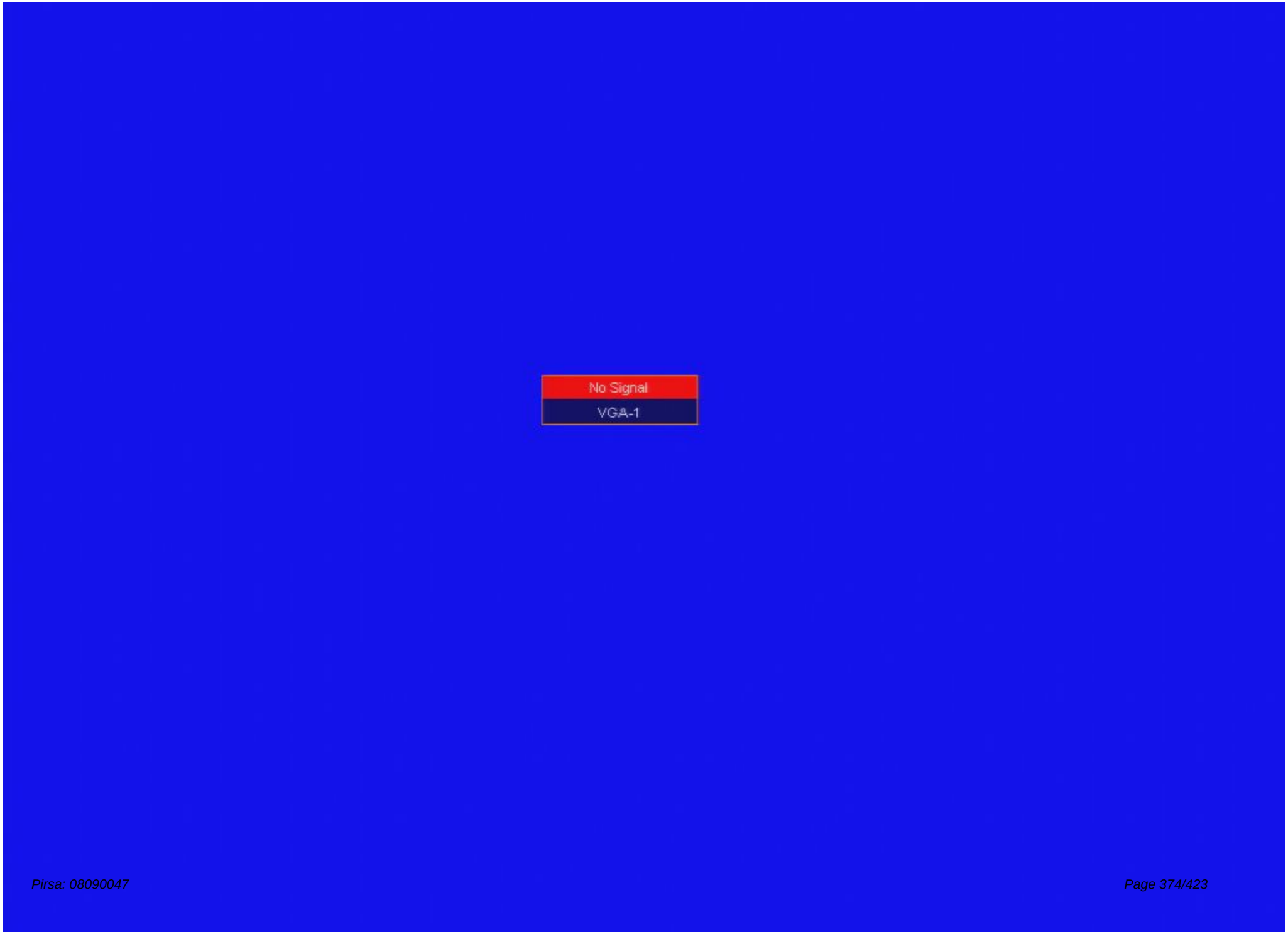

No Signal
VGA-1

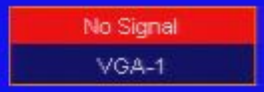

No Signal
VGA-1

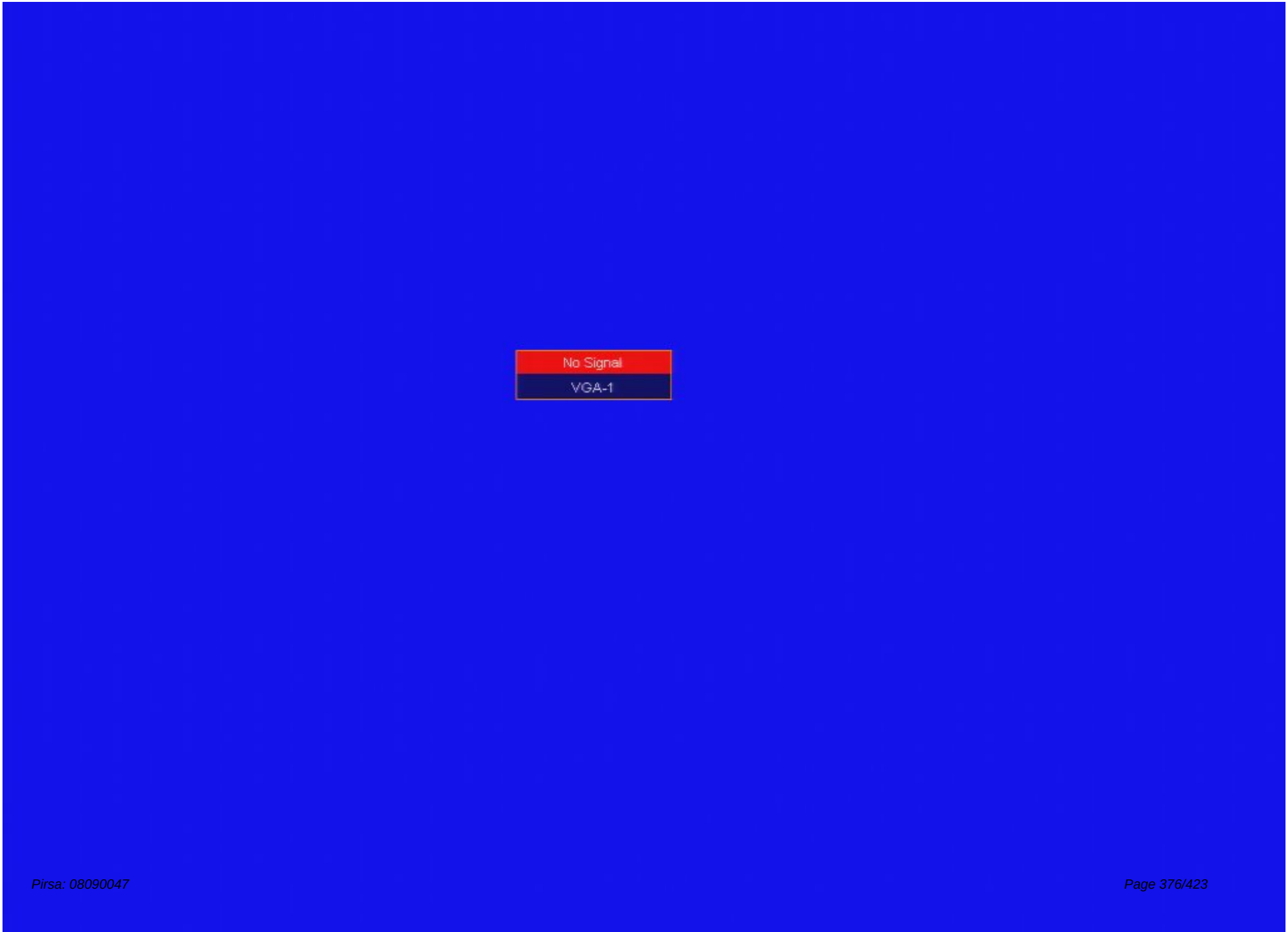

No Signal
VGA-1

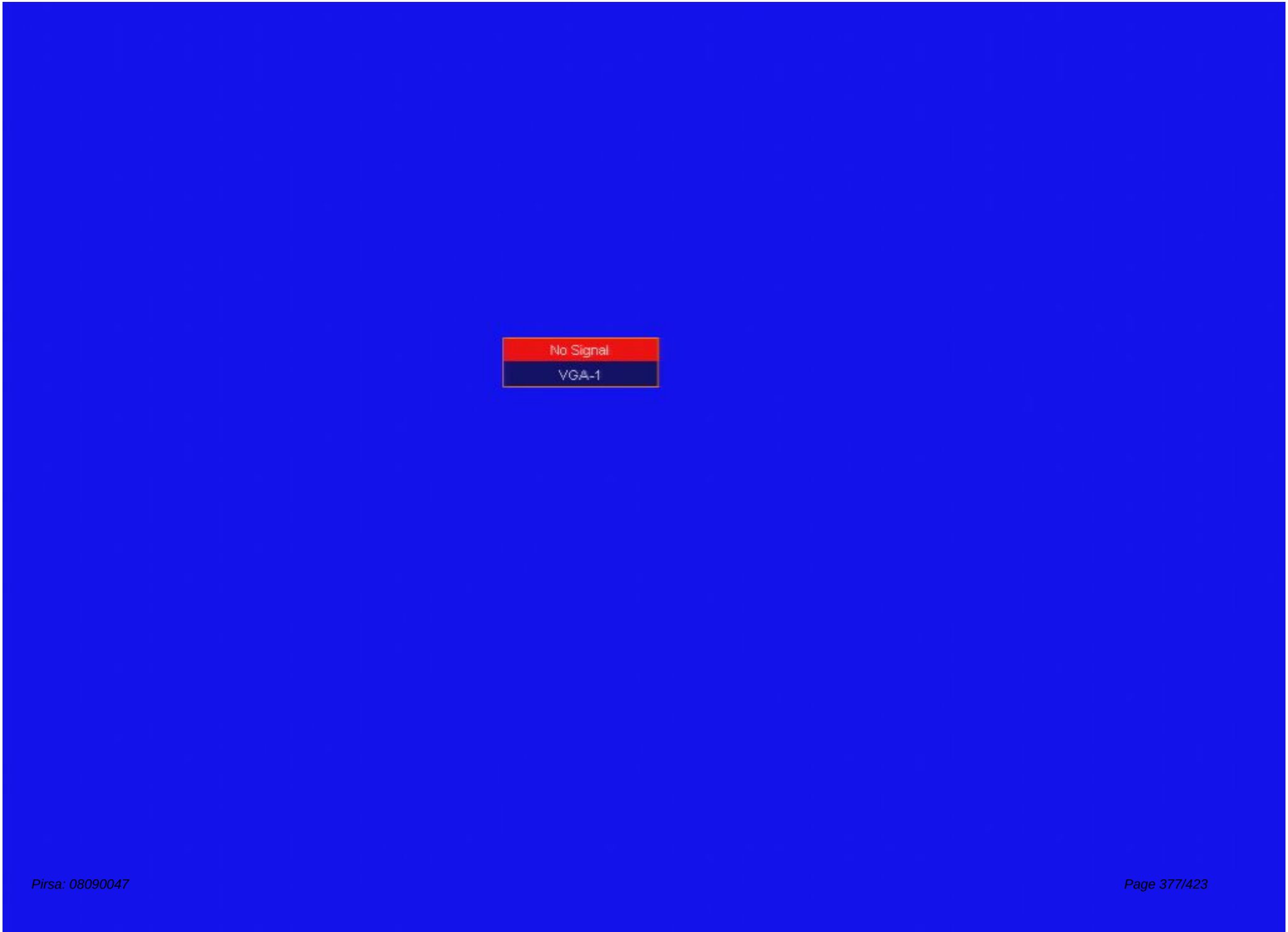

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

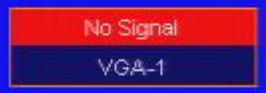

No Signal
VGA-1

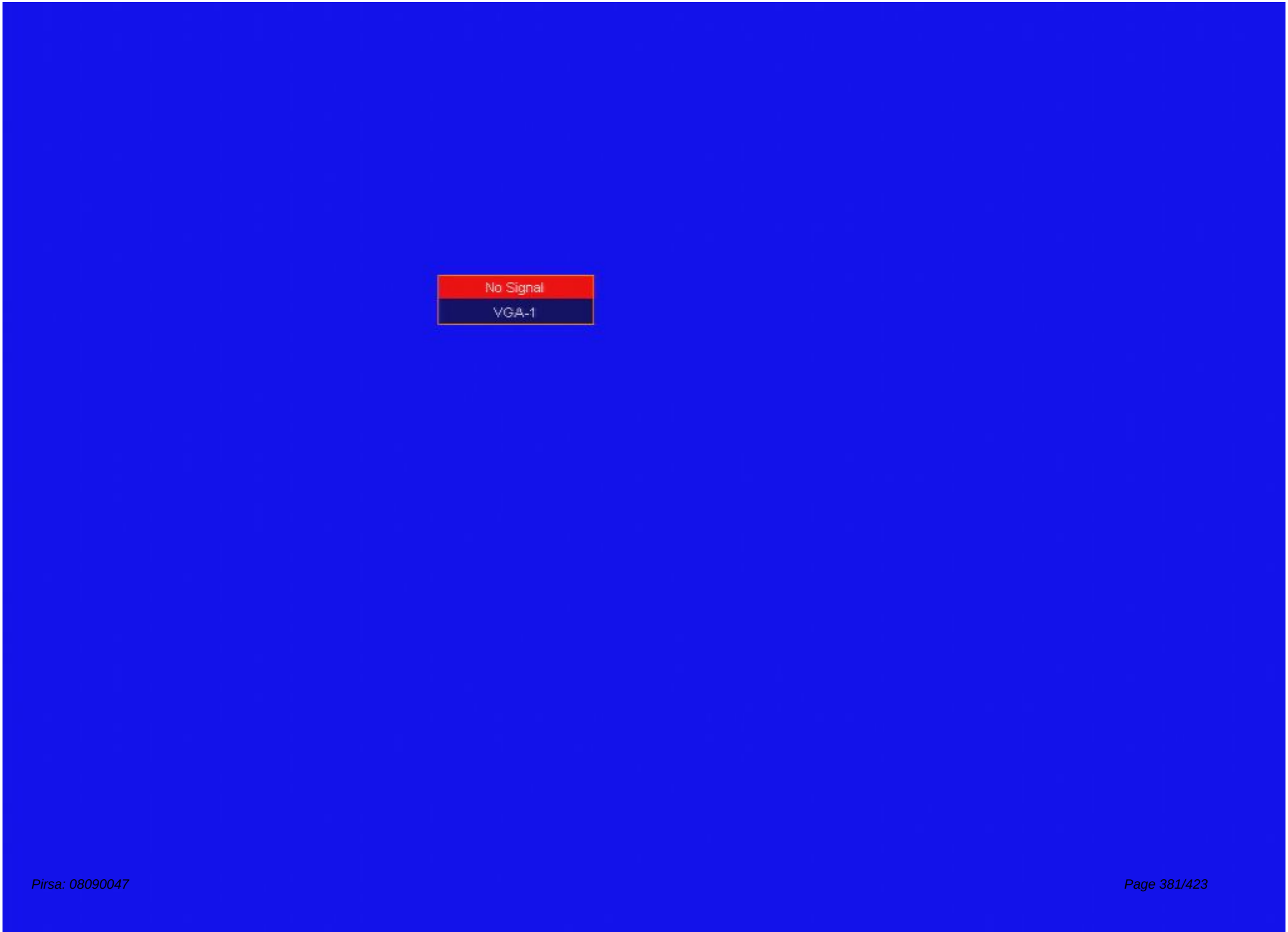

No Signal
VGA-1

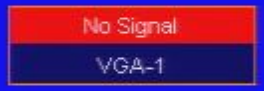

No Signal
VGA-1

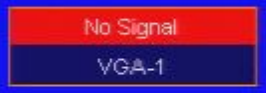

No Signal
VGA-1

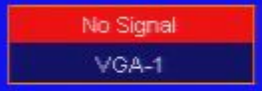

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

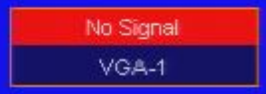

No Signal
VGA-1

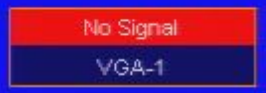

No Signal
VGA-1

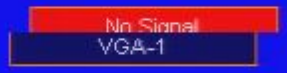

No Signal
VGA-1

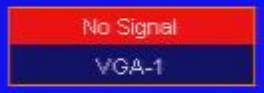

No Signal
VGA-1

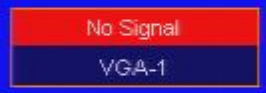

No Signal
VGA-1

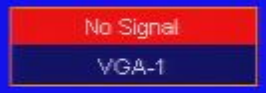

No Signal
VGA-1

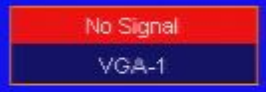

No Signal
VGA-1


No Signal
VGA-1

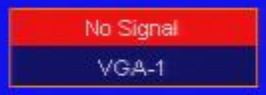

No Signal
VGA-1

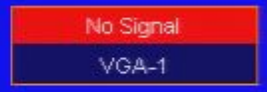

No Signal
VGA-1

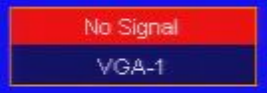

No Signal
VGA-1


No Signal
VGA-1

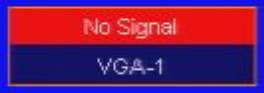

No Signal
VGA-1

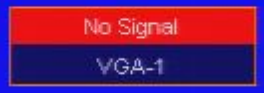

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1

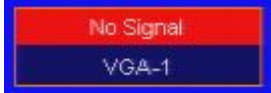

No Signal
VGA-1

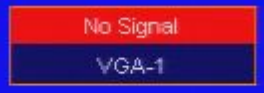

No Signal
VGA-1

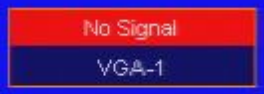

No Signal
VGA-1

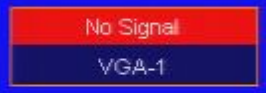

No Signal
VGA-1

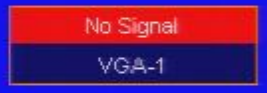

No Signal
VGA-1

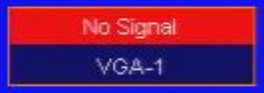

No Signal
VGA-1

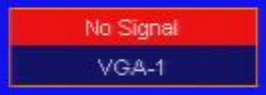

No Signal
VGA-1

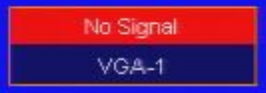

No Signal
VGA-1


No Signal
VGA-1

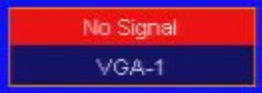

No Signal
VGA-1

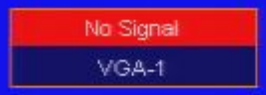

No Signal
VGA-1

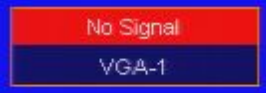

No Signal
VGA-1

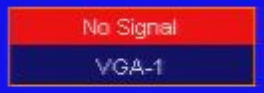

No Signal
VGA-1

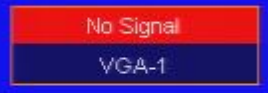

No Signal
VGA-1

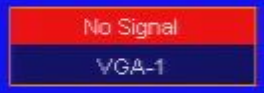

No Signal
VGA-1

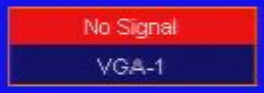

No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1