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An Information-Based Framework for Physical Measurability and Reconstructability

Version 0.9 · Preprint / Framework Paper · FORSCH-PROV0420 (number provisional) · as of 6 Oct 2026

Field	Entry
Author	Thomas Schüller (researcher), ORCID 0009-0003-9799-6747
Author imprint	Thomas Schüller · Syntagma Forschung · Vienna (no separate legal entity)
Affiliation	Independent researcher, no institutional affiliation
Correspondence	forschung@tschueller.com
Repository	forschung.tschueller.com · syntagma-science.com
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Field	Entry
Conflicts of interest	none
Licence	CC BY 4.0
Data status	no experimental raw data; ten numerical minimal models, reproducible (Section 14, Appendix C)
Source status	50 entries verified (publisher, standards register, full text), 12 flagged as open in Appendix I.2; these concern almost exclusively the edition and ISBN of textbooks and first editions
Track	FORSCHUNG (open channel, feeder). Tools run exclusively on the syntagma-science platform, see Appendix G

This version claims no new fundamental physics. It is an ordering framework for the measurability, reconstructability and falsifiability of physical measurement chains.

0 What changed relative to Version 0.8

Nothing in the work itself. No result, no proof, no figure and no appendix has changed. This version makes the bundle around the work ready for publication; the number is carried along so that work and bundle do not drift apart.

No.	Change	Reason
1	New VEROEFFENTLICHUNG.md in the main folder: the sequence in one place — the seven decisions that block everything, the order platform → deposit → journals, tick-off steps per track	the sequence was spread across the handover, the operations manual and the upload notes; when publishing you need it in one place
2	Landing page extended with legal matters : imprint, terms of use, privacy, separate licences for work and tool, liability note	without these a page is not publishable
3	Landing page extended with the network of brands	whoever cites, cites Syntagma; whoever licenses, buys from the responsible track. That was stated nowhere
4	Citation template in the author register corrected — it still read Version 0.3 — and extended with per-version check points	an outdated citation template produces wrong citations, permanently

The material is finished. What remains are the seven decisions in VEROEFFENTLICHUNG.md Section 1; all of them belong to the author and none can be derived from the material.

0.1 What had changed relative to Version 0.7

This version changes no result and no proof. It draws the disclosure line explicitly instead of presupposing it.

No.	Change	Reason
1	New Appendix G.6: self-protection and the disclosure line per REGEL-PROV0002	the work sits beside a paid offering; leaving that unstated leaves open whether something is being held back
2	For every component it is stated whether it is open and why — including what is not present at all	a claim without evidence would be advertising; evidence without a line would be a build manual
3	Checkability outranks protection is recorded as the precedence	a framework that cannot be refuted supports no offering
4	The choice for the browser tool is made and justified : MESSWERK stays open on the platform page	“in the browser” and “computing core internal” exclude each other; the rule requires a deliberate choice rather than a tacit one
5	REGEL-PROV0002 sits as its own file in the bundle; the adoption block now covers both rules	it governs all tracks, not only this project

Substantively unchanged: measurement chain, Theorems 1 and 2, classification A/B/C, numerics, experimental protocol, references, source checklist, licence levels, active/passive assignment.

0.2 What had changed relative to Version 0.6

This version changes no result and no proof. It anchors a cross-track rule that so far existed only as a decision.

No.	Change	Reason
1	New Appendix G.5: active and passive versions per REGEL-PROV0001	the line for what may go on a deposit was described for this project but not stated as a general rule
2	The borderline case of computation scripts is settled: they are passive and stay on the deposit	without them the work could not be checked, and checkability is the reason for depositing at all
3	The difference between free verification and the licensed tool is stated in G.5 rather than assumed	anyone verifying the numbers here does not need the tool; the tool computes on someone else’s measurement chain
4	The rule sits as its own file in the bundle (regelwerk/), with an adoption block for the central rulebook	it governs all projects, not only this one

Substantively unchanged: measurement chain, Theorems 1 and 2, classification A/B/C, numerics, experimental protocol, references, source checklist, licence levels.

0.3 What had changed relative to Version 0.5

This version changes no result and no proof. It converts the commercial arrangement to a platform-centred one.

No.	Change	Reason
1	Appendix G rewritten: syntagma-science is the destination, the open research channel the feeder	tools now run exclusively on the platform; Zenodo carries no tool, not even a preview build
2	Licence levels L0–L3 and six product classes per LIZ-PROV0001 added as Appendix G.2 and G.3	the assignment existed only as four service levels in the offering, not in the work itself
3	Appendix H reordered: platform → deposit → journals	a reference needs a destination; the platform has to exist before the deposit
4	Zenodo bundle prepared separately (Appendix H.2, folder <code>zenodo-upload/</code>)	the working bundle and the publication bundle are not the same; only the open material belongs on the deposit
5	Every deposit of the preprint carries the reference to syntagma-science	the preprint is a reach channel, not an end in itself

Substantively unchanged: measurement chain, Theorems 1 and 2, classification A/B/C, numerics, experimental protocol, references, source checklist.

0.4 What had changed relative to Version 0.4

This version changes no result and no proof. It folds in the source check that version 0.4 listed as the single remaining open task.

No.	Change	Reason
1	ISO 12233:2023 → ISO 12233:2024 in Section 19.3, Section 19.6 and Appendix D	the fifth edition supersedes the 2023 edition and also carries a changed title: “Digital cameras — Resolution and spatial frequency responses”
2	IEC TR 60825-14:2022 (Ed. 2.0) in place of the undated reference; status of IEC 60825-1 Ed. 4 noted	an undated normative reference is not reproducible in an experimental protocol
3	Mezghani, Antreich & Nossek (2010) : the conference paper WSA 2010, Bremen, 143–150, DOI 10.1109/WSA.2010.5456454 is now the primary source, arXiv:1010.5532 the preprint	the factor $2/\pi$ in class B now rests on the reviewed version
4	Kalman (1963) : journal name corrected to <i>Journal of the Society for Industrial and Applied Mathematics, Series A: Control</i>	<i>SIAM Journal on Control</i> is the later name of the same journal, not yet in use in 1963
5	Six missing DOIs added: Krener & Ide, Galiffi et al., Hansen, Janesick, Stadler, Amari (2016)	these had no identifier in v0.4, or only an unverified ISBN
6	Issue numbers added for ten entries (among them Paris, Bellman & Åström, Berreman, Shannon, Landauer, Hempel)	the page range alone does not identify the volume unambiguously

No.	Change	Reason
7	Appendix D converted into one continuous alphabetical list	the split into “DOI-verified” and “further sources” lost its purpose once the check was done
8	Appendix I restructured into I.1 verified, I.2 still open, I.3 what the check changed in the work	the reader should see the remaining gaps at a glance
9	Open entries reduced from 25 to 12 , verified entries from 23 to 50; those remaining concern almost exclusively the edition and ISBN of textbooks and first editions	the sources that carry content are now fully substantiated

What is still outstanding: the choice of edition for fourteen textbooks and three first editions, the edition status of JCGM 100/200 and EMVA 1288, and the access date of the SEP entry. These are itemised in Appendix I.2 and are to be closed before a journal version.

0.5 What had changed relative to Version 0.3

No.	Change	Reason
1	The gap claim is everywhere tied to the literature strands searched rather than stated absolutely	Integrity: the search was not exhaustive
2	Class C extended by three cases: EMCCD at low gain , quantisation outside the limiting cases, generally heteroscedastic noise	completeness of the classification
3	Section 5.5 extended by the noise coefficient (Chao, Ward & Ober) and the Stam inequality	two further neighbouring concepts requiring demarcation
4	New Section 7.1: Rayleigh and Sparrow as special cases of a threshold on d'	the Fisher information is the sharper criterion; the classical criteria can be placed rather than discarded
5	Convention for the excess noise factor stated explicitly	Robbins & Hadwen define $F_{\text{ENF}} = \sqrt{2}$, other works the squared quantity — without a convention the factors 2 and 1/2 are not traceable
6	Quantum bounds under noise (Escher et al.) and monotonicity of the quantum Fisher information under CPTP maps added	connects Section 13 to the data-processing inequality
7	New Appendix H: publication path , with a venue matrix and the arXiv endorsement rule changed on 21 January 2026	so far only noted in the handover
8	New Appendix I: source checklist with a status per entry	separates verified from unverified references traceably

No.	Change	Reason
9	References extended by twelve entries	Chernoff, Amari (2001), Chao et al., Hyncek & Nishiwaki, Mortensen et al., Escher et al., Paris, Gan & Law, Aspden et al., Worrall, Earman & Norton, Stadler

0.6 What had changed relative to Version 0.2

No.	Change	Reason
1	The core statement is explicitly identified as observational equivalence in the sense of Rothenberg (1971) and no longer framed as an own finding	Literature check: the statement has been standard since 1971. The contribution lies in the transfer to physical measurement chains, not in the statement
2	The separability criterion is formulated as Theorem 1 with an equivalence proof instead of being asserted	On a connected product domain, $\partial^2 \log F / \partial p_i \partial p_j = 0$ is equivalent to the product form
3	Sharper formulation via stage efficiencies $\eta_k = F_k / F_{k-1}$ (Theorem 2)	The telescoping identity $F_n = F_0 \prod \eta_k$ is trivial. The real claim is that η_k depends only on its own stage's parameters
4	Classification of forward models into three classes with evidence and counterexamples (Section 5.6)	The open question from v0.2 is thereby settled for the main channel classes
5	Demarcation from parameter orthogonality (Cox & Reid 1987) and from cascaded-detector theory (DQE)	These are the closest literature strands; the DQE literature explicitly denies the general product form
6	Four new numerical minimal models M7–M10 with Figures 6–9	Stage efficiency, separability map, qubit dephasing, slit experiment
7	Complete experimental protocol for the optical slit experiment (Section 19)	v0.2 named the experiment only as an open item
8	New section Vienna lineage and the philosophy of measurability (Section 16)	Mach, Boltzmann, Bridgman, Vienna Circle, Schrödinger, modern measurement theory
9	New section demarcation from observability theory (Section 17)	Kalman and Hermann–Krener are the closest competing formulation
10	References extended with DOIs; Appendix F states what was not found in the literature	Positioning of the contribution

Abstract

This work formulates an information-based ordering framework for physical measurability and reconstructability. The claim is not to introduce new fundamental physics but to organise established concepts from wave theory, electrodynamics, scattering theory, signal theory, digitisation and quantum measurement along a common measurement chain:

$$X_0 \rightarrow H_{\text{field}} \rightarrow H_{\text{mat}} \rightarrow H_{\text{mix}} \rightarrow H_{\text{measure}} \rightarrow Q \rightarrow Y.$$

The starting point is observational equivalence: if $p(Y|\theta_1) = p(Y|\theta_2)$ for $\theta_1 \neq \theta_2$, unique reconstruction from that channel is excluded. This is not new; it is the definition of identifiability of a parametric model, and its local version has been equivalent to regularity of the Fisher information matrix since Rothenberg (1971). The contribution of this work lies in two points.

First, the diagnostic working quantity K is defined as an effective signal-to-noise ratio and derived exactly from the Fisher information for the scalar Gaussian channel: with $K := \theta^2 F(\theta)$ one obtains $K = \text{SNR} \cdot C^2$. Second, the product form

$$K = \text{SNR} \cdot G(|q|a) \cdot D_{\text{mat}} \cdot \gamma \cdot R_{\text{dir}} \cdot C^2$$

receives a testable validity criterion: on a connected product domain it is exact precisely when $\log F$ is additively separable. Stated more sharply via stage efficiencies $\eta_k = F_k/F_{k-1}$, the claim is that each η_k depends only on the parameters of its own stage. This is decided for three classes of forward models: multiplicative transmission with single-stage noise and Poisson thinning satisfy the criterion exactly; high-gain EMCCDs and low-SNR one-bit quantisation satisfy it asymptotically; multi-stage noise injection, the crossover between shot and read noise, nonlinearity and saturation violate it.

Ten numerical minimal models with a fixed random seed support the statements, among them a separability map over signal level and read noise and a fully computed optical slit experiment. The scientific load-bearing capacity lies in the falsification conditions.

Keywords: measurability; reconstructability; identifiability; observational equivalence; Fisher information; separability; cascaded systems; wave-vector transfer; coherence; inverse problems; quantum measurement.

1 Introduction

Physical measurements are often described through single terms: signal strength, frequency, wavelength, reflection, resolution, noise, detection. These are necessary but not sufficient. A strong signal may say little about the state sought. A local null signal may arise from destructive interference. A digitally crisp result may rest on coarse quantisation or algorithmic priors. A reflected signal may carry energy while having lost direction and phase.

The central question is therefore not whether a signal exists, but:

Which state information is distinguishable in the signal under the given physical and instrumental conditions?

The contribution is not a new law of nature. It is a framework that orders existing physical descriptions along the question of measurability and — since version 0.2 — states the conditions under which the working quantity used is admissible. Version 0.3 answers that question for the main channel classes.

2 Scope of claim

The model claims no new fundamental physics. It replaces neither Maxwell’s equations, nor quantum mechanics, scattering theory, Fourier optics, information theory, nor the theory of inverse problems. It is an ordering framework whose purpose is to make the measurement question explicit:

1. Which state is to be distinguished?
2. Which physical forward chain generates the signal?
3. Which factors preserve or destroy state information?
4. Which states remain distinguishable in the measurement channel?
5. Which states collapse into the same measurement distribution?

3 Measurement chain

$$X_0 \rightarrow H_{\text{field}} \rightarrow H_{\text{mat}} \rightarrow H_{\text{mix}} \rightarrow H_{\text{measure}} \rightarrow Q \rightarrow Y. \tag{1}$$



Jede Stufe kann Zustandsinformation erhalten, umformen oder vernichten.
Every stage can preserve, transform or destroy state information.

Messbarkeitskriterium / measurability criterion: $p(Y | \theta_1) \neq p(Y | \theta_2)$
Das Messergebnis ist nicht der Zustand. / The result is not the state.

Figure 1: Figure 1: Operator sequence of the measurement chain. The result is not the state itself but the outcome of physical and informational transformations.

Symbol	Meaning
X_0	physical initial state
H_{field}	field or wave propagation
H_{mat}	material response: reflection, transmission, absorption, scattering, dispersion
H_{mix}	mixing, multiple scattering, mode coupling, nonlinearity, linear time variance
H_{measure}	measurement process, detector response, measurement operator
Q	quantisation, thresholding, classification, digital decision
Y	registered result

In the linear case $Y = H_{\text{total}}X_0 + N$ with $H_{\text{total}} = H_m \cdots H_1$ (2). If H_{total} has a null space, different states produce the same signal. In the nonlinear case $Y = F_m(\dots F_1(X_0)) + N$ (3), and local sensitivity decides.

4 State distinguishability

A signal carries state information about θ if

$$p(Y|\theta_1) \neq p(Y|\theta_2) \quad \text{for } \theta_1 \neq \theta_2, \quad (4)$$

and unique reconstruction is excluded if

$$p(Y|\theta_1) = p(Y|\theta_2), \quad \theta_1 \neq \theta_2. \quad (5)$$

Provenance of the statement. Equation (5) is the definition of *observational equivalence* of two parameter values; a model is identifiable if no two distinct parameter values are observationally equivalent. Rothenberg (1971) shows that under weak regularity conditions local identifiability is equivalent to non-singularity of the Fisher information matrix. This work adopts that theorem and applies it to physical forward chains. The contribution lies in the transfer and in the stage decomposition, not in the statement itself.

Three levels must be separated:

Level	Criterion	Quantity
measurability in principle	$p(Y \theta_1) \neq p(Y \theta_2)$	identifiability
practical reconstructability	overlap of distributions	Kullback–Leibler divergence, d'
robust technical estimability	achievable variance	Fisher information, Cramér–Rao

In the quantum case the Fisher information is replaced by the quantum Fisher information; Braunstein and Caves (1994) show that the statistical distinguishability of neighbouring states defines a Riemannian metric on the space of density operators.

5 The working quantity K

5.1 Definition as effective SNR

K is defined as the **effective signal-to-noise ratio** of the equivalent Gaussian channel that yields the same Fisher information about θ as the measurement chain under consideration.

Hence

$$I_{\text{eff}} = \log_2(1 + K) \quad (6)$$

is, in the anchor case, not an approximation but exactly the Shannon capacity of the equivalent channel.

5.2 Anchor case: derivation from the Fisher information

For $Y = s(\theta) + N$, $N \sim \mathcal{N}(0, \sigma^2)$, $F(\theta) = (\partial_\theta s)^2 / \sigma^2$ (7). With the dimensionless definition $K := \theta^2 F(\theta)$ and

$$SNR := \frac{s^2}{\sigma^2}, \quad C := \frac{\theta}{s} \frac{\partial s}{\partial \theta}$$

it follows exactly that

$$K = SNR \cdot C^2. \quad (8)$$

K is therefore the Fisher information with respect to $\ln \theta$, and C is the logarithmic sensitivity (elasticity) of the forward chain. If the further stages act as amplitude-scaling factors $g_i \in [0, 1]$ without changing noise power, then $SNR_{\text{eff}} = SNR \prod_i g_i^2$ and

$$K = SNR \cdot G(|q|a) \cdot D_{\text{mat}} \cdot \gamma \cdot R_{\text{dir}} \cdot C^2. \quad (9)$$

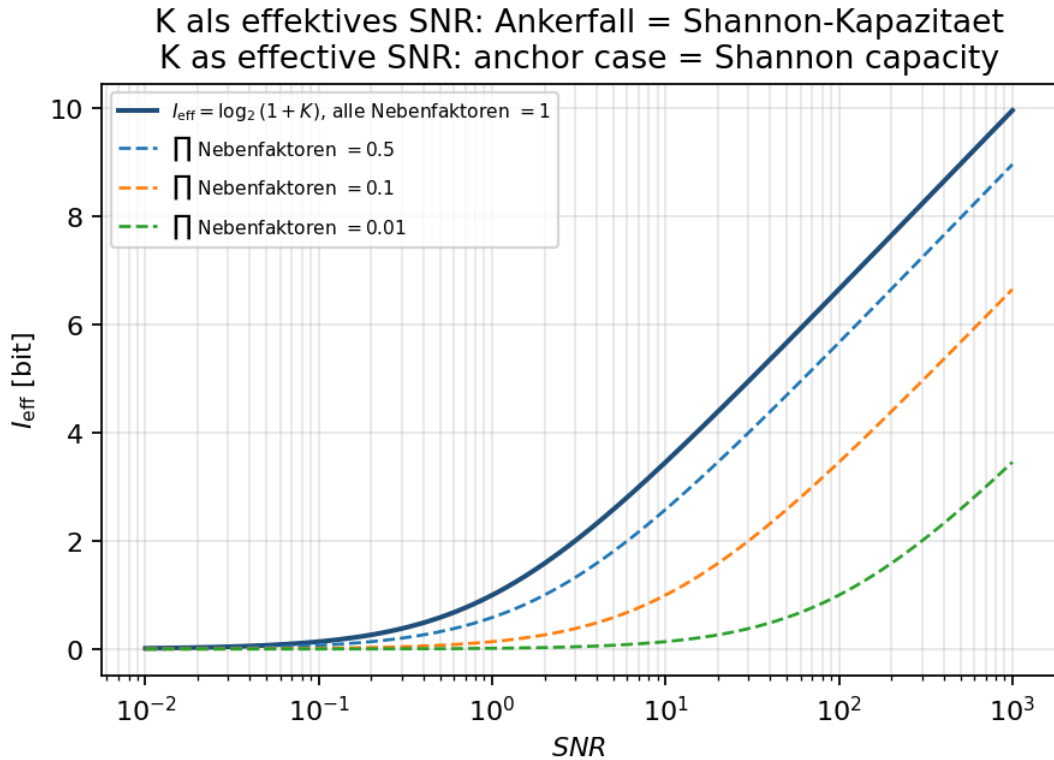


Figure 2: Figure 2: K as effective SNR. The anchor case — all secondary factors equal to one — is exactly the Shannon capacity of the equivalent Gaussian channel.

Factor	Meaning	Range
SNR	signal-to-noise ratio of the carrier	≥ 0
$G(q a)$	resolution or structure-transfer factor	$[0, 1]$
D_{mat}	material and propagation factor	$[0, 1]$
γ	coherence factor, $\gamma = g^{(1)} $	$[0, 1]$
R_{dir}	bearing-information factor	$[0, 1]$
C	normalised state-signal coupling	real

5.3 Theorem 1 (separability)

Let $F(\theta; p_1, \dots, p_n)$ be positive and twice continuously differentiable on a connected product domain $P_1 \times \dots \times P_n$. Then the following are equivalent:

1. $F = \prod_{i=1}^n f_i(p_i)$ for suitable functions $f_i > 0$;
2. $\frac{\partial^2 \log F}{\partial p_i \partial p_j} = 0$ for all $i \neq j$. **(10)**

Proof (sketch). (1) $\Rightarrow$ (2): $\log F = \sum_i \log f_i(p_i)$; each summand depends on exactly one variable, so all mixed second derivatives vanish. (2) $\Rightarrow$ (1): if all mixed second derivatives of a C^2 function vanish on a connected product domain, then $\partial \log F / \partial p_i$ is a function of p_i alone; integration yields $\log F = \sum_i h_i(p_i) + \text{const.}$ $\square$

The criterion is therefore not sufficient or necessary but **equivalent** to the product form. It is invariant under coordinatewise reparametrisations $p_i \mapsto \varphi_i(p_i)$, but not under mixing transformations. Whether, for a given model, a mixing reparametrisation exists that makes $\log F$ separable is a boundary-value problem of the same kind as the orthogonalisation of Cox and Reid (1987); it remains open.

5.4 Theorem 2 (stage formulation)

For a chain $\theta \rightarrow X_0 \rightarrow X_1 \rightarrow \dots \rightarrow X_n$ with Fisher informations F_k about θ , the telescoping identity always holds:

$$F_n = F_0 \prod_{k=1}^n \eta_k, \quad \eta_k := \frac{F_k}{F_{k-1}} \in [0, 1]. \quad (11)$$

The bound $\eta_k \leq 1$ follows from the data-processing inequality for Fisher information (Zamir 1998). Identity (11) is therefore trivial and by itself carries no content. The substantive claim of the framework is:

The stage efficiency η_k depends only on the parameters p_k of its own stage — not on upstream parameters $p_{<k}$ and not on the signal level.

Only in this form is the product form a testable physical statement about channel structure. It is equivalent to Theorem 1 applied to the parameter groups of the individual stages.

5.5 Demarcation from neighbouring concepts

Concept	Object	Relation to the criterion
Parameter orthogonality (Cox & Reid 1987)	off-diagonal $i_{\theta\lambda}$ of the Fisher matrix between interest and nuisance parameter	Logically independent: $F_{\theta\theta}$ may factorise in p while $i_{\theta p} \neq 0$, and vice versa. Only the reparametrisation question is shared
Data-processing inequality (Zamir 1998)	F does not increase along a Markov chain	Gives $\eta_k \leq 1$, but no product rule
Stam inequality, chain rule	$1/J(X+Y) \geq 1/J(X) + 1/J(Y)$ and additive decompositions	Additive, not multiplicative: information adds inversely, not as a product

Concept	Object	Relation to the criterion
Noise coefficient (Chao, Ward & Ober 2012)	ratio of the pixelwise Fisher information to the ideal Poisson case	Closest to the criterion: an efficiency per stage. But defined signal-dependently and silent about the cascade — exactly the gap Theorem 2 closes
Noise-figure cascade (Friis 1944)	$F = F_1 + (F_2 - 1)/G_1 + \dots$	Additive with gain weighting — the standard case of a violation
Cascaded detectors, DQE (Rabbani, Shaw & Van Metter 1987; Cunningham & Shaw 1999)	signal and noise power spectra per stage	Closest chain decomposition. It works with second moments rather than Fisher information and states that the DQE of a cascaded system is generally not a multiplicative cascade of individual DQEs

5.6 Classification of forward models

Class	Forward model	Criterion (10)	Evidence
A — exact	multiplicative transmission $s = s_0(\theta) \prod a_i(p_i)$, noise from exactly one stage, σ^2	satisfied	$\log F = 2 \log \partial_\theta s_0 + \sum 2 \log a_i - \log \sigma^2$
A — exact	parameter-independent Poisson with thinning, $\lambda = \lambda_0(\theta) \prod \eta_i$	satisfied	binomial thinning preserves the Poisson form; $F = (\lambda_0'^2/\lambda_0) \prod \eta_i$
B — asymptotic	EMCCD at high gain	satisfied with constant factor 1/2	excess noise factor $\rightarrow \sqrt{2}$ (Robbins & Hadwen 2003)
B — asymptotic	one-bit quantisation at low SNR	satisfied with factor $2/\pi$	Mezghani, Antreich & Nossek (2010), WSA, DOI 10.1109/WSA.2010.5456454
C — violated	noise injected at several stages, $\sigma^2 = \sum_k \sigma_k^2 \prod_{j>k} a_j^2$	violated	Friis structure; cross terms between a_j and σ_k
C — violated	crossover between shot and read noise, $\sigma^2 = \text{ENF}^2 \lambda + \sigma_r^2$	violated in the crossover	numerically in Section 14.7
C — violated	aperture limitation: G and R_{dir} both depend on d	violated	double counting of the same physical resource
C — violated	nonlinear characteristic, saturation	violated; at saturation $F = 0$	$F = h'(s)^2 s'^2 / \sigma^2$ with $h' \rightarrow 0$
C — violated	gain-dependent noise $\sigma^2 = \sigma_0^2(1 + \eta g^2)$	violated	numerically in Section 14.4
C — violated	EMCCD at low gain	violated	the excess noise factor depends on G and the effective read noise is σ_r/G ; G acts on signal and noise term at once
C — violated	quantisation outside the limiting cases, medium to high SNR	violated	the loss factor then depends on SNR, no longer on the quantiser alone

Class	Forward model	Criterion (10)	Evidence
C — violated	generally heteroscedastic noise $\sigma^2(s)$	violated	additional term per Equation (12)

This three-class assignment rests on the literature strands searched — data-processing inequality, cascaded systems, quantisation, detector noise — and claims no completeness over all conceivable channel classes.

The general reason for class C fits in one line: for $Y \sim \mathcal{N}(s(\theta), \sigma^2(\theta))$,

$$F = \frac{(\partial_\theta s)^2}{\sigma^2} + \frac{(\partial_\theta \sigma^2)^2}{2\sigma^4}. \quad (12)$$

The second term is absent from $K = \text{SNR} \cdot C^2$. As soon as one parameter acts on both signal and noise, it contributes to both terms and the factors are no longer independently calibratable.

Convention for the excess noise factor. Robbins and Hadwen (2003) define the excess noise factor as an amplitude quantity with $F_{\text{ENF}} \rightarrow \sqrt{2}$ at high gain; other works, such as Mortensen et al. (2010), already quote the squared quantity. This work consistently carries the **squared quantity** ENF^2 as a variance factor: the variance grows by ENF^2 , the Fisher information falls by $1/\text{ENF}^2$. For a high-gain EMCCD this gives $\text{ENF}^2 \rightarrow 2$ and the factor $1/2$ in class B.

6 Direction and signed flux

Direction is determined relative to an axis, aperture, source, detector or interface. For a wave with wave vector k and observation axis e :

$$c_e = \frac{k \cdot e}{|k|}. \quad (13)$$

For two counter-propagating components along e the signed direction balance is

$$\Phi_e = \frac{|A_+|^2 - |A_-|^2}{|A_+|^2 + |A_-|^2}, \quad K_\Phi = K \cdot \Phi_e. \quad (14)$$

Φ_e is not a new quantity but the net flux normalised to total power. With reflection coefficient $\Gamma = A_-/A_+$ and standing-wave ratio $s = (1 + |\Gamma|)/(1 - |\Gamma|)$, exactly

$$\Phi_e = \frac{1 - |\Gamma|^2}{1 + |\Gamma|^2} = \frac{2s}{1 + s^2}. \quad (15)$$

Φ_e is thus a rescaled VSWR reading, directly measurable in any RF laboratory (checked numerically in 14.5).

7 Resolution and wave-vector transfer

$$q = k_{\text{out}} - k_{\text{in}}, \quad |q|a \gtrsim 1, \quad |q| = 2k \sin(\Theta/2). \quad (16)$$

Near-field methods, structured illumination, nonlinearity, repeated measurements or priors extend this bound. They are not violations of the model but additional information channels that must be entered into the chain explicitly.

7.1 Rayleigh and Sparrow as thresholds on d'

The classical resolution criteria of Rayleigh, Sparrow and Abbe are formulated for incoherent point sources and impose a fixed threshold: resolved or not. The Fisher information knows no such threshold; it falls continuously. Both descriptions can be reconciled rather than played off against each other.

For two point sources at separation Δ , locally $d'^2 \approx F(\Delta) \Delta^2$, and d' is the normalised separability of detection theory. A classical criterion is then the statement that d' reaches a particular value:

Criterion	classical form	form within the framework
Rayleigh	the first minimum of one diffraction pattern falls on the maximum of the other	d' exceeds a threshold depending on photon count and noise model
Sparrow	the dip between the maxima vanishes	a stricter threshold on the same quantity
Abbe	$ q a \gtrsim 1$	$G(q a)$ falls below a value at which K drops under one bit

The gain of this reformulation is practical: the classical criteria know nothing of photon count. They say the same for an image with ten photons and one with ten million. The Fisher form says how many photons are needed for two states to become distinguishable at a given aperture — and that is the question actually asked in design.

8 Material response and information loss

$R+T+A=1$ is an **energy balance, not an information balance**. A mirror preserves directed information; a matte surface may return a similar amount of light while diffusing direction and phase. D_{mat} describes how much of the signal structure usable for the state question arrives ordered at the detector.

9 Interference, cancellation and standing waves

$$\Psi = \sum_j A_j \exp[i(k_j \cdot x - \omega_j t + \phi_j)], \quad |\Psi|^2 = A_1^2 + A_2^2 + 2A_1 A_2 \cos(\Delta k \cdot x - \Delta \omega t + \Delta \phi). \quad (17)$$

Destructive interference means that field contributions add vectorially to zero at the point considered. A local null signal is not a global proof of absence.

10 Linear superposition, linear time variance and nonlinear mixing

Medium class	New field frequencies?	Mechanism
linear, time-invariant (LTI)	no	pure superposition
linear, time-varying (LTV)	yes	parametric coupling to the modulation
nonlinear	yes	mixing products, intermodulation

Morgenthaler (1958) solves Maxwell’s equations for media with time-dependent permittivity and permeability and shows that the fields remain linear when the medium parameters do not respond to field strength, yet a monochromatic wave undergoes a frequency deviation. Parametric amplifiers, modulators, switched plasmas and time-modulated metamaterials (Galiffi et al. 2022) belong to this class. With $Y = \alpha X + \beta X^2 + \gamma_3 X^3 + \dots$, by contrast, mixing products $f_1 \pm f_2$ and intermodulation $2f_1 - f_2$ arise.

11 Electromagnetic core

$$\nabla \cdot D = \rho, \quad \nabla \cdot B = 0, \quad \nabla \times E = -\partial_t B, \quad \nabla \times H = J + \partial_t D. \quad (18)$$

In the linear, isotropic, local limit $D = \varepsilon E$, $B = \mu H$, $J = \sigma E$. In anisotropic, dispersive, nonlinear or time-dependent media, ε , μ , σ must be modelled as tensors, frequency functions, convolution kernels or nonlinear response functions. In this section μ denotes permeability only; the coherence factor is γ .

12 Digitisation

If Q is pure post-processing of the same analogue signal, the data-processing inequality holds:

$$I(X; Y_{\text{digital}}) \leq I(X; Y_{\text{analog}}). \quad (19)$$

Digitisation creates no physical state information that is contained neither in the analogue signal nor in additional data, priors or further measurements.

13 Quantum measurement

$$p(y|\theta) = \text{Tr}(\rho_\theta E_y), \quad E_y \geq 0, \quad \sum_y E_y = I. \quad (20)$$

The corresponding estimation bound is the quantum Cramér–Rao bound (Helstrom 1969); the distinguishability metric is formulated by Braunstein and Caves (1994), with $F_Q = \max_{\text{POVM}} F_C$. An accessible overview for applications is given by Paris (2009).

The quantum Fisher information is monotone under completely positive, trace-preserving maps; this is the quantum form of the data-processing inequality of Section 12 and the reason $\eta_k \leq 1$ also holds in the quantum case. For estimation bounds under noise there is a general framework (Escher, de Matos Filho & Davidovich 2011); under dephasing the attainable scaling falls back asymptotically to $1/\sqrt{N}$ and the Heisenberg advantage is lost. Decoherence means that phase relations become practically inaccessible through coupling to detector or environment; one then considers $\rho_S = \text{Tr}_E(\rho_{SE})$. All purifications of a reduced state are related by unitaries on the ancilla (Hughston, Jozsa & Wootters 1993): infinitely many total states yield the same local statistics. That is the quantum case of Equation (5).

14 Numerical minimal models

Figures from `werkzeuge/FORSCH-PROV0420_minimalmodelle_v0.2_2026-08-26_numerik.py` (seed 20260826, models M1–M6) and `..._v0.3_2026-10-05_numerik.py` (seed 20261005, models M7–M10). Raw results: `ergebnisse.json` and `ergebnisse_v0.3.json`.

14.1 M1 — Gaussian channel, Fisher information, Cramér–Rao

Model $Y = A\theta + N$, $A = 1.0$, $\sigma = 0.5$, $\theta_0 = 1.0$, $n = 200,000$.

Quantity	Value	Check
F analytic	4.000	—
F Monte Carlo (score variance)	3.991	deviation 0.23 %
Cramér–Rao $1/F$	0.2500	—
empirical variance of the ML estimator	0.2494	deviation 0.23 %
$K = \text{SNR} \cdot C^2$	4.000	identical to $\theta^2 F$
$I_{\text{eff}} = \log_2(1 + K)$	2.322 bit	Shannon anchor
F at coupling $C = 0$	0	Equation (5)

14.2 M2 — Null space and conditioning continuum

$H = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$, $\sigma = 0.1$: Fisher eigenvalues $\{0; 100; 200\}$, null-space direction $(0.707; -0.707; 0)$. Replacing the exact null space by a small singular value ϵ , the Cramér–Rao bound grows as $1/\epsilon$ (from 0.1 at $\epsilon = 1$ to $\approx 1.0 \cdot 10^5$ at $\epsilon = 10^{-6}$).

What decides is the singular-value spectrum relative to the noise level — the Picard condition of inverse-problem theory (Bertero & Boccacci 1998).

14.3 M3 — Two-sensor bearing model

$\tau = d \sin \theta / v$, $v = 343$ m/s, $\sigma_\tau = 2$ μ s, $n = 40,000$ per point.

d [m]	θ [°]	σ_θ Monte Carlo [°]	σ_θ analytic [°]	$F(\theta)$
0.00	any	—	—	0
0.05	0	0.787	0.786	$5.31 \cdot 10^3$
0.05	30	0.906	0.908	$3.98 \cdot 10^3$
0.05	60	1.590	1.572	$1.33 \cdot 10^3$
0.20	0	0.197	0.197	$8.50 \cdot 10^4$
0.20	30	0.227	0.227	$6.37 \cdot 10^4$
0.20	60	0.395	0.393	$2.12 \cdot 10^4$

Median relative deviation 0.20 %, maximum 3.4 %.

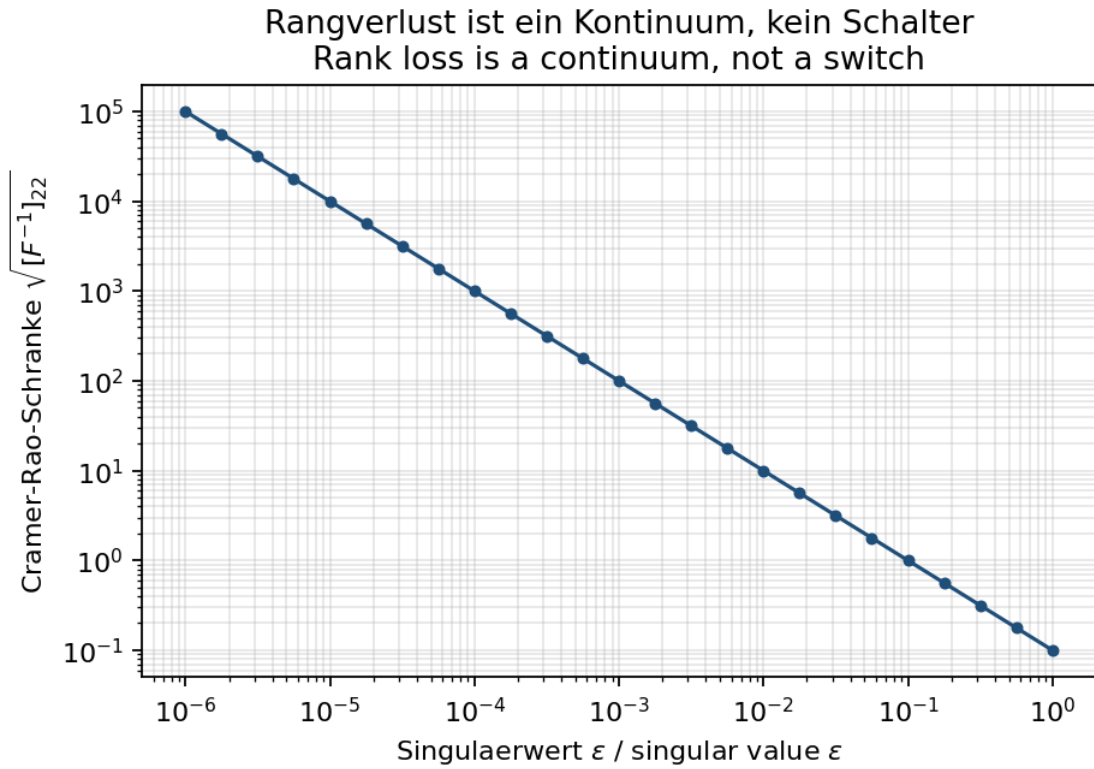


Figure 3: Figure 3: Rank loss is a continuum, not a switch.

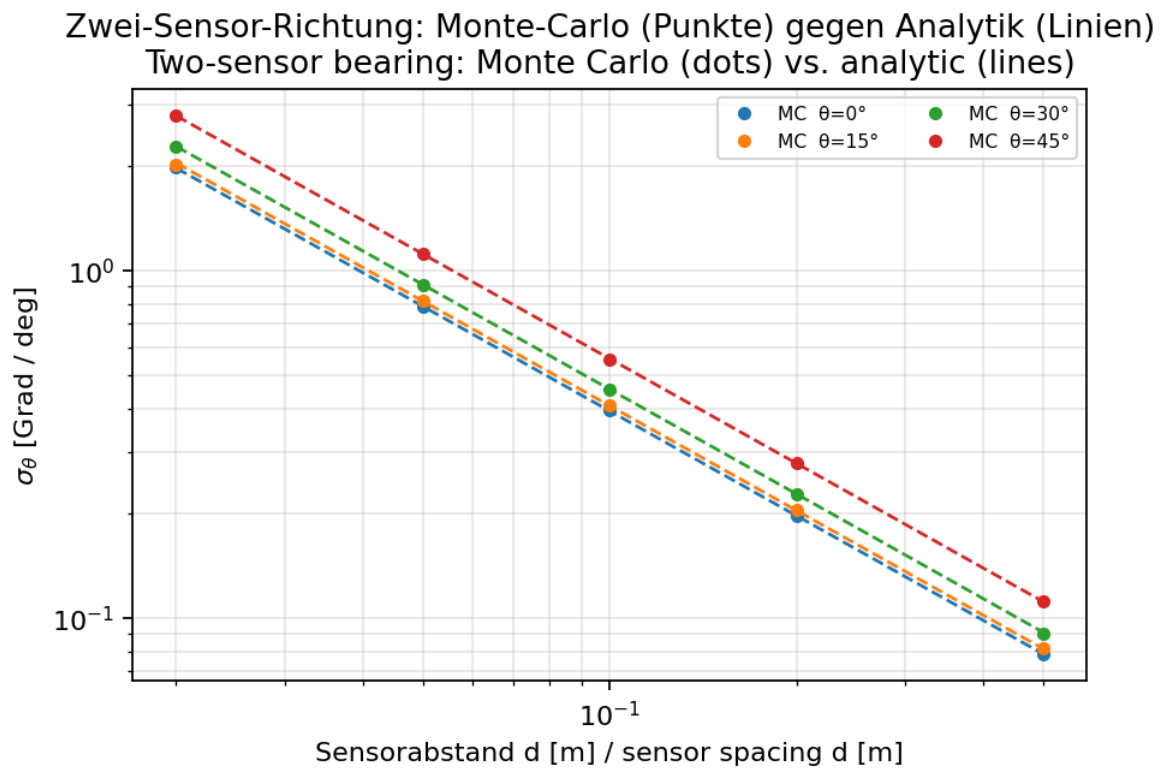


Figure 4: Figure 4: Two-sensor bearing; $d = 0$ yields no bearing information.

14.4 M4 — Breakdown of the product form under gain-dependent noise

$\sigma^2(g) = \sigma_0^2(1 + \eta g^2)$, $\sigma_0 = 0.2$, $\eta = 0.05$. The true Fisher information saturates at 500; the product form calibrated at $g_0 = 1$ grows as g^2 .

Gain g	Behaviour	Relative deviation
0.1 ... 1.71	product form usable	< 10 %
10	product form overestimates	436 %

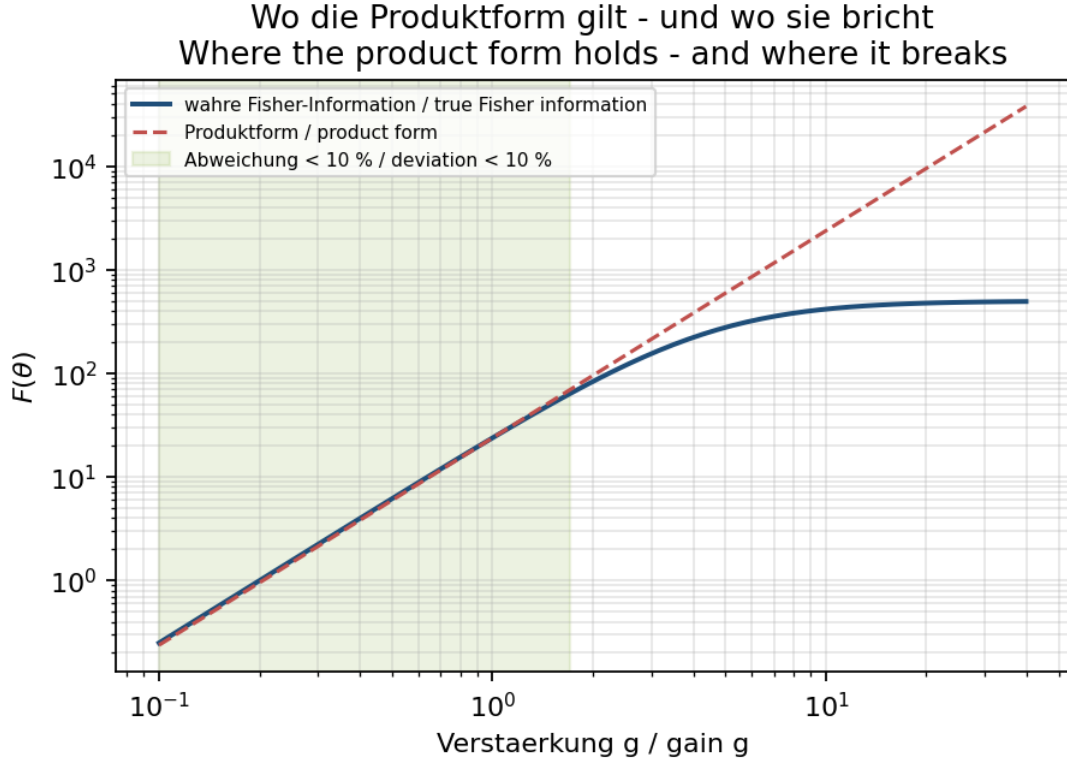


Figure 5: Figure 5: Validity range of the product form.

14.5 M5 — Signed flux balance and standing-wave ratio

Identity (15) checked over $|\Gamma| \in [0; 0.999]$; maximum deviation $2.2 \cdot 10^{-16}$ (machine precision).

$ \Gamma $	VSWR s	Φ_e
0.0	1.0	1.000
0.2	1.5	0.923
0.5	3.0	0.600
$\rightarrow 1$	$\rightarrow \infty$	$\rightarrow 0$

14.6 M7 — Stage efficiency in a cascade

Poisson source $\theta = 1000$ photoelectrons, three transmission stages with nominal $\eta = (0.80; 0.60; 0.50)$, read noise σ_r at the end of the chain. Measured: $\eta_k^{\text{eff}} = F_k / F_{k-1}$.

σ_r [e ⁻]	η_1^{eff}	η_2^{eff}	η_3^{eff}	maximum deviation from nominal transmission
0	0.800	0.600	0.500	0.0005
5	0.795	0.588	0.477	0.023
50	0.679	0.399	0.272	0.228
200	0.643	0.363	0.252	0.249

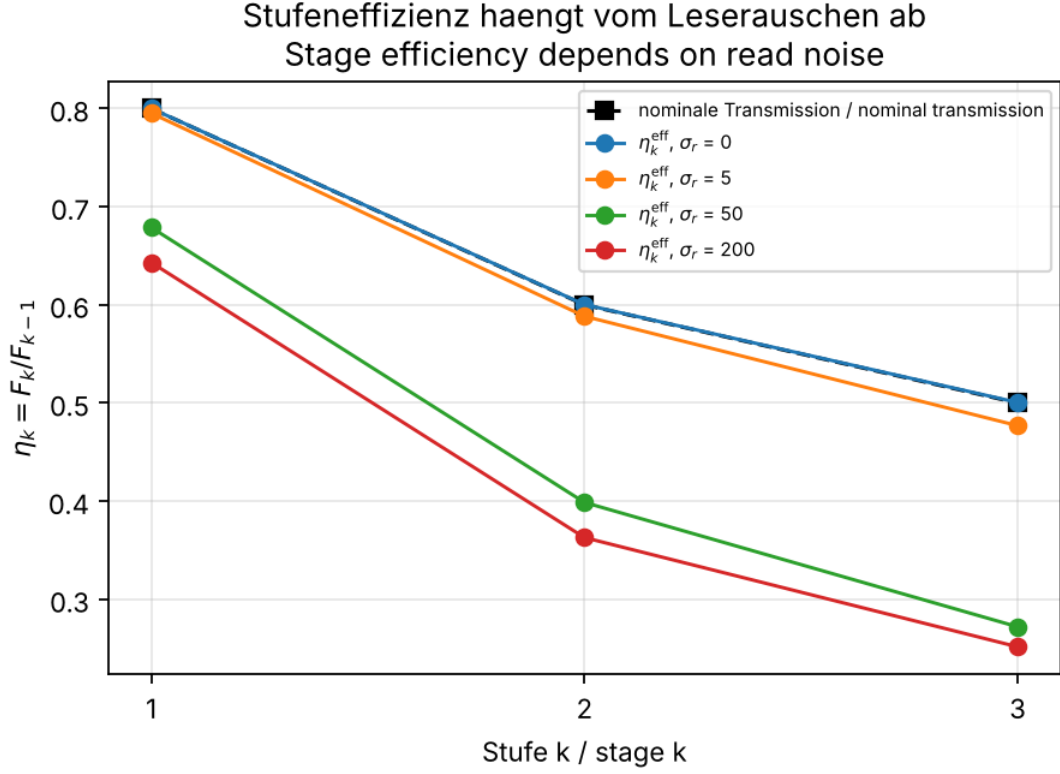


Figure 6: Figure 6: Stage efficiency ceases to be a property of the stage alone once noise is injected at the end of the chain.

This is Theorem 2 in numbers. Without read noise, η_k^{eff} is exactly the nominal transmission of its own stage and the product form holds. With read noise, η_3 depends on how much signal stages 1 and 2 left behind — the stage efficiency is then no longer a stage property, and the factors cannot be calibrated separately.

14.7 M8 — Separability map

Mixed second derivative $\partial^2 \log F / \partial \ln \lambda \partial \ln \sigma_r$ over signal level and read noise, grid 120×120 over $\lambda \in [1; 10^5]$ e⁻ and $\sigma_r \in [0.1; 300]$ e⁻.

λ [e ⁻]	σ_r [e ⁻]	$ \partial^2 \log F $	Regime
10	1.0	0.173	crossover
10	102	0.002	read-noise limited
962	1.0	0.002	shot-noise limited
962	9.7	0.163	crossover
100,000	9.7	0.002	shot-noise limited
100,000	102	0.178	crossover

At a threshold of 0.05, 58 % of the parameter area considered is separable. The structure is instructive: separability holds in the two asymptotic regimes — clearly shot-limited or clearly read-limited — and breaks

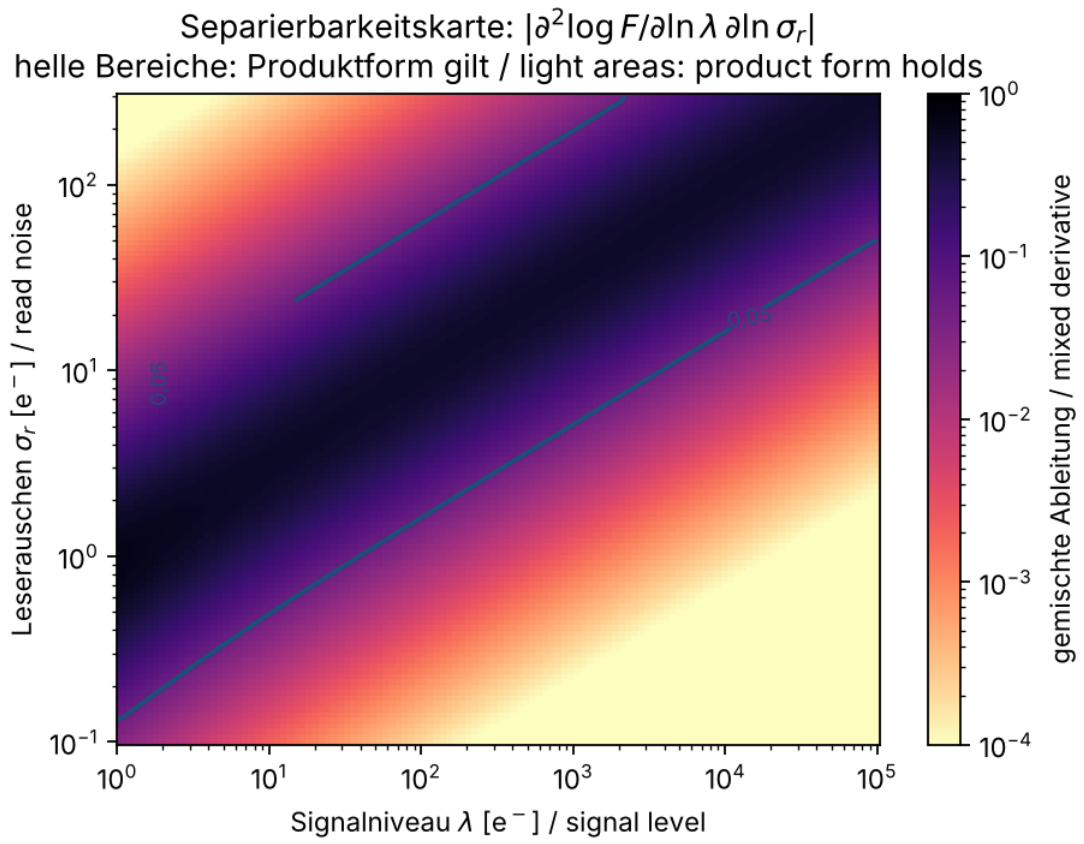


Figure 7: Figure 7: Separability map. In the light regions the product form is admissible; in the dark diagonal band it is not.

in the crossover band $\lambda \approx \sigma_r^2$. The product form is therefore not an either/or but a property of the operating point. In practice: factorisation is admissible where one noise contribution clearly dominates.

14.8 M9 — Qubit under dephasing

State $\rho = \frac{1}{2}(I + r(\cos \varphi \sigma_x + \sin \varphi \sigma_y))$ with $r = e^{-\Gamma t}$, $\Gamma = 1$.

Quantity	Value
$F_Q(\varphi)$	$r^2 = e^{-2\Gamma t}$
$F_Q(\omega)$ for $\varphi = \omega t$	$t^2 e^{-2\Gamma t}$
optimal single duration at fixed total time, theoretical	$t^* = 1/(2\Gamma) = 0.500$
same quantity, numerical	0.500
F_Q at t^*	0.3679
F_C of a projective measurement at $\varphi - \alpha = 90^\circ$	0.3679 (attains F_Q to grid resolution $4 \cdot 10^{-6}$)
F_C at $\varphi - \alpha = 0^\circ$	0

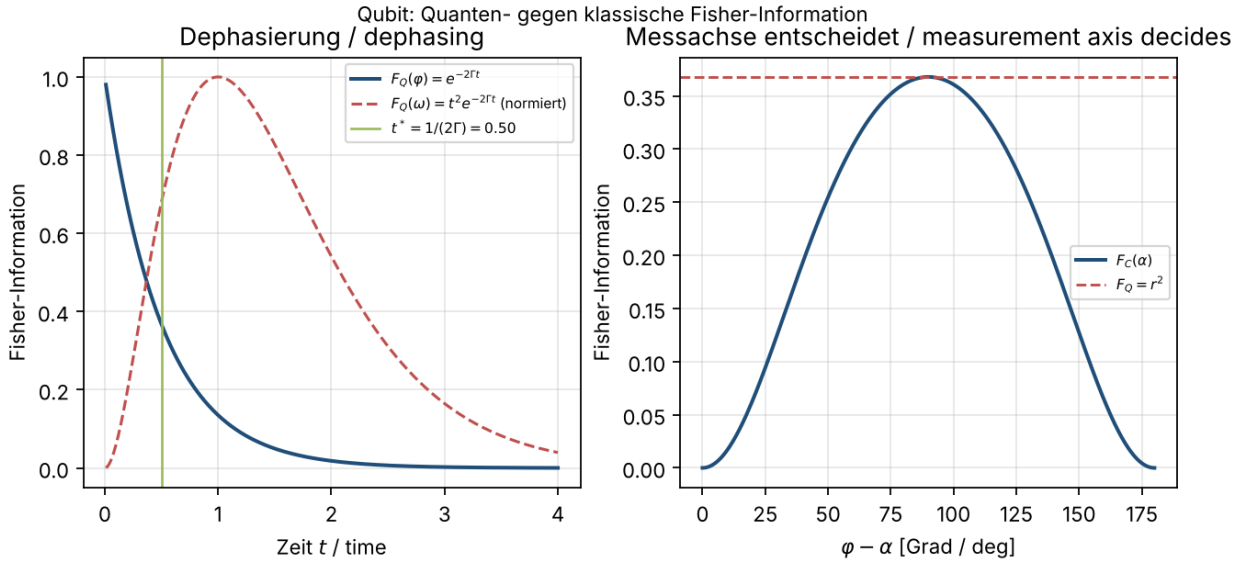


Figure 8: Figure 8: Quantum versus classical Fisher information. The measurement axis decides whether the attainable information is exploited.

Two lessons for the framework. First, non-distinguishability in the quantum case is **measurement-relative**: at $\varphi - \alpha = 0$, $F_C = 0$ although $F_Q > 0$ — the information is present in the state and inaccessible in the chosen channel. Second, $\log F_Q(\omega) = 2 \log t - 2\Gamma t$ with $\partial^2/\partial t \partial \Gamma = -2 \neq 0$ shows that the separability criterion is violated in the parameters (t, Γ) but satisfied in $(t, D = e^{-\Gamma t})$. Admissibility of the product form depends on the choice of parametrisation.

14.9 M10 — Slit experiment, fully computed

Single slit, $a_0 = 150 \mu\text{m}$, $\lambda = 650 \text{ nm}$, $L = 1.00 \text{ m}$, pixel $1.55 \mu\text{m}$, 4096 pixels, read noise 3 e^- , conversion $1 \text{ e}^-/\text{ADU}$, peak signal 4000 e^- , pixel integration with 16 nodes.

Quantity	Value
Fraunhofer number $a^2/(\lambda L)$	0.035 (condition satisfied)
position of $ q a = 1$	0.690 mm
first minimum	4.333 mm
Fisher information $F(a)$	$7.86 \cdot 10^{14} \text{ m}^{-2}$
Cramér–Rao bound σ_a	35.7 nm

Quantity	Value
Monte-Carlo standard deviation of the ML estimator ($n = 2000$)	35.2 nm
Cramér–Rao efficiency	1.03

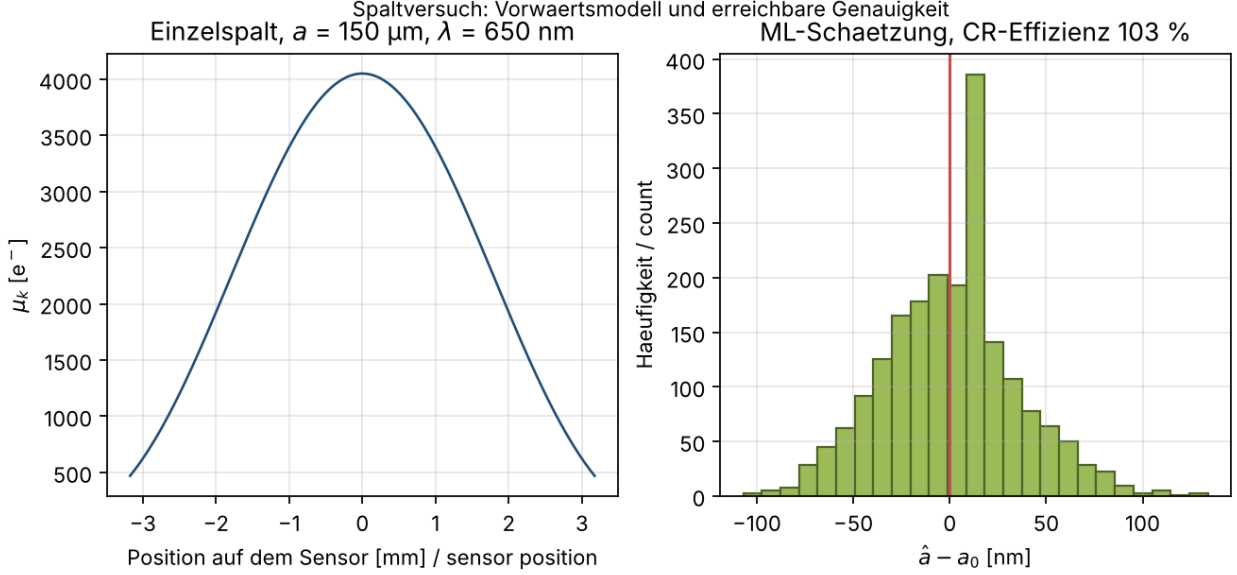


Figure 9: Figure 9: Forward model of the slit experiment and attainable accuracy of slit-width estimation.

With this setup the slit width is estimable to about 36 nm, i.e. $2.4 \cdot 10^{-4}$ of its value. The decisive point for the experimental programme: accuracy is limited by photon statistics and model fidelity, not by pixel size.

For empirical testing of the separability criterion, the dependence on exposure and read noise serves:

Exposure (scale factor)	$F(a)$ at $\sigma_r = 1$	at $\sigma_r = 3$	at $\sigma_r = 10$	at $\sigma_r = 30$
0.1	$7.89 \cdot 10^{13}$	$7.29 \cdot 10^{13}$	$4.12 \cdot 10^{13}$	$9.35 \cdot 10^{12}$
1.0	$7.92 \cdot 10^{14}$	$7.86 \cdot 10^{14}$	$7.20 \cdot 10^{14}$	$4.31 \cdot 10^{14}$
10	$7.93 \cdot 10^{15}$	$7.92 \cdot 10^{15}$	$7.85 \cdot 10^{15}$	$7.26 \cdot 10^{15}$

At high exposure F is essentially proportional to exposure and independent of read noise — the product form holds. At low exposure the two parameters couple: the drop from $\sigma_r = 1$ to 30 is a factor of 8.4 there, but only 1.09 at tenfold exposure. Exactly this mixed dependence is measurable in the laboratory and is the test plan of Section 19.

15 Falsifiability

No.	Falsification case	Status v0.3
1	Structure information at $ q a \ll 1$ without near field, nonlinearity, priors, repeated measurement or a super-resolution mechanism	unchanged
2	Bearing reconstruction from a signal with $p(Y k_1) = p(Y k_2)$ without an additional channel	numerically demonstrated in 14.3

No.	Falsification case	Status v0.3
3	New field frequencies in a demonstrably linear and time-invariant medium without nonlinear detection	LTV media excepted (Section 10)
4	Stable interference with genuinely absent coherence	unchanged
5	Reconstruction of lost analogue information from pure quantisation without additional information	unchanged
6	Energy or information balance that cannot be closed by reflection, transmission, absorption, scattering, frequency conversion or internal degrees of freedom	unchanged
7	Product form (9) holds in a system in which criterion (10) is demonstrably violated	testable per 14.7 and Section 19
8	New: a stage efficiency η_k stays constant across variation of upstream parameters although the noise model shows multi-stage injection	would refute Theorem 2

16 The Vienna lineage and the philosophy of measurability

The framework stands in a tradition that begins in Vienna and leads via operationalism to modern model-based measurement theory. This placement is not decoration: it decides what the criterion may claim.

Position	Core thesis	Standard criticism	What carries over
Mach (<i>Analysis of Sensations</i> 1886; economy of thought)	Physical concepts are economical summaries of elements; atoms are dispensable	Planck 1908/09; later confirmation of atomism by Perrin and Einstein	Economy of thought as minimal parametrisation — but no restriction to the observable, since θ may be theoretical
Boltzmann (picture theory, <i>Populäre Schriften</i> 1905)	Theories are pictures or models; several pictures may represent the same phenomena	—	Non-identifiability is precisely this model pluralism in statistical form. Boltzmann is the closest ancestor of the framework
Bridgman (<i>The Logic of Modern Physics</i> 1927)	A concept is synonymous with the corresponding set of operations	Every new measurement method creates a new concept; theoretical terms remain unexplained	The framework avoids the trap: θ is defined model-theoretically, the channel is only the test instance. The core statement is an exclusion criterion , not a definition of meaning

Position	Core thesis	Standard criticism	What carries over
Vienna Circle: Carnap (<i>Testability and Meaning</i> 1936/37), Neurath, Schlick	Verifiability or confirmability criterion of meaning	Hempel 1950: too strict for universal statements, too liberal under disjunction	What carries: Carnap's shift from verifiability to gradual confirmability — the counterpart to K as a graded measure. What does not: a criterion of meaning for sentences
Schrödinger (1935)	Entanglement; the expectation catalogue of a subsystem is incomplete	—	Information resides only in the total state: Section 13
Tal, <i>Measurement in Science</i> (SEP); model-based measurement theory	Measurement is process plus model; indication and measurement outcome must be separated	—	The framework is a model-based theory: Y = indication, $\hat{\theta}$ = outcome, $p(Y \theta)$ = model
Representational theory of measurement (Krantz, Luce, Suppes & Tversky 1971)	Measurement as homomorphism of empirical into numerical relations; uniqueness theorems	presupposes observable relations	Uniqueness theorems correspond to the equivalence classes of observational equivalence
GUM (JCGM 100:2008), VIM	Uncertainty propagation with sensitivity coefficients $c_i = \partial f / \partial x_i$	linearisation	C is a normalised sensitivity coefficient; $1/F$ corresponds to Type A uncertainty at the Cramér–Rao bound
Underdetermination (Duhem, Quine 1951); gauge freedom	Data do not determine theories uniquely; gauge directions are physically redundant	—	Gauge directions are exact null directions of the Fisher matrix; the identifiable structure is the quotient

Position of the framework. It is a model-based, information-metric measurement theory. From Mach it takes economy, from Boltzmann model pluralism, from Carnap gradation. It avoids operationalism because it does not define meaning via operations but only excludes what no channel can distinguish. The classical objection to Mach — atoms were not directly observable and exist nonetheless — does not apply: atoms were identifiable through suitable channels, such as Brownian motion. **Non-identifiability is channel-relative, not absolute.** That sentence is the philosophical point of the framework and at the same time its safeguard against any positivist overreach.

17 Demarcation from observability theory and neighbouring frameworks

Framework	Object	Stochastic	Graded	Physical chain decomposition	Relation
Hadamard, Tikhonov, Bertero & Boccacci	well-posedness, regularisation	partly	via singular values	no	non-identifiability corresponds to the kernel of the forward operator
Identifiability (Koopmans; Rothenberg 1971)	observational equivalence	yes	locally via the Fisher matrix	no	supplies the core statement; no novelty here

Framework	Object	Stochastic	Graded	Physical chain decomposition	Relation
Estimation theory (Kay 1993; Van Trees 1968)	Cramér–Rao, Fisher information	yes	yes	no	supplies $K = \theta^2 F$
Kalman observability	rank of the observability matrix	no	binary	no	in the linear-Gaussian case the Fisher information of the initial state is the R^{-1} -weighted observability Gramian; full rank $\Leftrightarrow F$ regular
Hermann & Krener (1977)	local weak observability, rank condition on Lie derivatives	no	binary	no	differential version; null directions are non-identifiable directions
Empirical Gramians, measures of unobservability (Krener & Ide 2009)	graded observability	partly	yes	no	closest graded competitor
Structural identifiability (Bellman & Åström 1970)	parameters from ideal data	no	binary	no	limiting case $SNR \rightarrow \infty$
Practical identifiability, profile likelihood (Raue et al. 2009)	finite, noisy data	yes	yes	no	methodologically closest
Cascaded DQE theory	signal and noise power per stage	yes	yes	yes	closest chain decomposition; denies the general product form

Clean demarcation. Kalman and Hermann–Krener observability answer whether states are distinguishable from noise-free output trajectories of a dynamical system. The present framework asks how much information about θ each physical stage of a static or quasi-static measurement chain transmits under noise, and whether that transmission factorises stagewise. In the linear-Gaussian case the rank condition and the regularity of the Fisher matrix coincide; this equivalence is cited here as known and not presented as a result.

New relative to all of these are three points: the assignment of stages to physical sub-theories, the criterion for admissibility of the product form, and the treatment of the quantum stage with the distinction between POVM-bound and attainable information.

18 Real-world examples

Example	Lesson for measurability
mirror vs. matte wall	reflected energy is not directed information
clear vs. frosted glass	transparency is not structure transfer
microphone array	direction arises from time or phase differences, not from a local level
radar (civil: navigation, weather)	range, Doppler and bearing are different information channels
sonar (civil: bathymetry, fisheries)	multipath can supply information or create ambiguity
eddy-current testing	a defect is reconstructed via altered electromagnetic reaction, not seen
digital camera	a pixel value is the outcome of optics, sensor, gain, quantisation and processing; saturation destroys information
double slit	which-path information and interference capability must be described via measurement operators and coherence
parametric amplifier	new frequencies without nonlinearity; time variance is a channel of its own
cooled vs. uncooled camera	the same sensor moves between shot- and read-limited regimes — and thus between separable and non-separable

19 Experimental protocol: optical slit experiment

The protocol is designed to be feasible in a workshop with 3D printing, a laser diode and a camera sensor, without laboratory equipment. It tests two things: the structure-transfer factor $G(|q|a)$ and the separability criterion.

19.1 Setup

Component	Specification	Rationale
Light source	laser diode 635–650 nm, Class 2 (≤ 1 mW)	fully sufficient with ND filters; Class 2 keeps the EN 60825-1 effort low
Slits	commercial slit set or two razor blades on a micrometer stage, 50–300 μm	FDM and resin printing give no defined edges below 100 μm
Distance	$L = 1.00$ m, measured to ± 2 mm	Fraunhofer condition $a^2/(\lambda L) \ll 1$, here 0.035
Sensor	monochrome CMOS with RAW output, known pixel pitch	a Bayer matrix otherwise halves effective sampling
Tube and baffles	3D printed, matte black, several stray-light baffles	stray light creates offset and lowers modulation
Neutral filters	ND series	exposure series without changing the geometry

19.2 Calibration before measuring

1. **Photon-transfer curve** per EMVA 1288: determine conversion gain g , read noise σ_r , linearity and full well. The result is the noise model $\sigma^2(\mu) = \mu/g + \sigma_r^2$ that carries every subsequent Fisher computation.
2. **Linearity**: use RAW only; gamma correction and JPEG processing turn the model into a nonlinear characteristic and violate the criterion in class C.
3. **Pixel scale**: check against the data sheet and additionally against a grating of known constant.
4. **Dark frames** at the same temperature and exposure time.
5. **System MTF** per ISO 12233:2024 — explicitly with **LED illumination**, not with the laser: the standard presupposes incoherent imaging; under coherent illumination different cut-off frequencies apply and edges show ringing.

19.3 Measurement series

Series	Variation	Purpose
R1	slit width a in 6–8 steps from 50 to 300 μm	$G(q a)$ over the range $ q a = 0 \dots 10$
R2	exposure time over 3 decades at fixed a	signal level λ
R3	gain or read noise in 3–4 steps	σ_r
R4	30 repetitions per operating point with realignment	reproducibility and empirical variance

19.4 Evaluation

1. Set up the forward model $\mu_k(a)$ as the pixel integral of sinc^2 , not the point formula.
2. Estimate a per frame by maximum likelihood; compare the empirical variance against $1/F(a)$ (Cramér–Rao efficiency). The simulation in 14.9 expects $\sigma_a \approx 36 \text{ nm}$ at $a = 150 \mu\text{m}$.
3. From $R2 \times R3$, record the surface $\log F(\ln \lambda, \ln \sigma_r)$ and form the **mixed second differences**. Expectation per 14.7: near zero in the shot- and read-limited regimes, clearly non-zero in the crossover.
4. From R1, plot the structure-transfer factor as the ratio of measured to ideal contrast over $|q|a$.

19.5 Expected results and falsification

The framework is supported if the mixed derivative differs significantly from zero in the crossover and not in the asymptotes. Theorem 2 would be refuted if stage efficiencies stayed constant across all operating points although the photon-transfer curve shows multi-stage noise injection.

19.6 Laser safety

Regulation	Content
EN 60825-1:2014 + A11:2021 (IEC 60825-1:2014 Ed. 3.0 + AMD1/AMD2:2017)	classification and accessible emission limits; Class 2 in the visible up to 1 mW. An IEC 4th edition is in preparation and not yet published
IEC TR 60825-14:2022 (Ed. 2.0)	user guidance, hazard assessment
ISO 12233:2024	resolution and spatial frequency response; supersedes the 2023 edition and carries a changed title
Directive 2006/25/EC, in Austria VOPST	workplace exposure limits
EN 208	alignment eyewear for the visible range

Anyone who alters or removes the optics of a classified laser module must reclassify and counts as a manufacturer under the standard. Exact limits are to be taken from the standard’s tables, not from secondary sources.

20 Discussion

The utility of the framework lies in systematically separating signal, energy, information, direction, material response and decision. A bright image is not automatically information-rich. A null signal is not automatically absence. A digital reconstruction is not automatically physically unique.

Relative to version 0.2 the contribution shifts a second time. There, K was derived but the validity of the product form was open. Here it is decided for the main channel classes, and the result is less comfortable than the product form suggests: factorisability is not a property of the system but of the **operating point**. The same camera is separable in bright light and not at dusk. That is not a weakness of the presentation but a statement about measurement chains, and it is measurable.

The mathematical core remains the measurement distribution $p(Y|\theta)$. K is a diagnostic tool for engineering use, not the theoretical core.

21 Limits

First, this is not a new fundamental theory. Second, the core statement is not new but adopted. Third, outside the Gaussian anchor case K is an approximation. Fourth, the classification in Section 5.6 is not exhaustive; it covers the channel classes examined. Fifth, distinguishability in principle does not guarantee practical reconstructability. Sixth, information here means physical state distinguishability, not meaning. Seventh, all ten minimal models are simulations with known forward models; the experiment of Section 19 is planned, not performed. Eighth, the literature search was limited: “not found in the literature” does not mean “does not exist”. Ninth, not every reference has been verified at the work itself; Appendix I flags the open entries individually.

22 Conclusion

Measurability is distinguishable state dependence within a real physical measurement chain. The starting point — $p(Y|\theta_1) = p(Y|\theta_2)$ excludes unique reconstruction — is the observational equivalence of identifiability theory and is adopted here, not claimed. The own contribution is the stage decomposition of a physical measurement chain and the criterion stating when it may be collapsed multiplicatively.

The shortest version: **measurability is distinguishable state dependence — and the product form holds exactly as far as its factors do not secretly contain one another. Whether they do is decided by the operating point, not by the instrument.**

Appendix A — Symbol table

Symbol	Meaning
X_0, θ, Y	initial state, parameter to be estimated, measurement result
$H_{\text{field}}, H_{\text{mat}}, H_{\text{mix}}, H_{\text{measure}}, Q$	chain operators and decision stage
SNR	signal-to-noise ratio
q, a	wave-vector transfer, structure size
$G(q a)$	structure-transfer factor
C	normalised state–signal coupling (elasticity); enters as C^2
D_{mat}	material and propagation factor
γ	coherence factor $ g^{(1)} $ (was μ in v0.1)
R_{dir}	bearing-information factor
c_e	direction cosine (was s_e in v0.1)
Φ_e	signed direction balance (was S_e in v0.1)
K, K_Φ	effective SNR $\theta^2 F(\theta)$; signed version
$F(\theta), F_Q$	Fisher information, quantum Fisher information
η_k	stage efficiency F_k/F_{k-1}
Γ, s	reflection coefficient, standing-wave ratio
ENF	excess noise factor. Convention: carried here throughout as the variance factor ENF^2 ; Robbins & Hadwen (2003) define the amplitude quantity $F_{\text{ENF}} = \sqrt{2}$

Appendix B — Validity ranges of central formulas

Formula	Valid for	Caution with
$\lambda = v/f$	harmonic waves with defined phase velocity	strong dispersion
$ k = 2\pi/\lambda$	plane or locally plane waves	strongly localised fields
$q = k_{\text{out}} - k_{\text{in}}$	scattering, reflection, diffraction with definable wave vectors	strongly diffuse fields

Formula	Valid for	Caution with
$ q a \gtrsim 1$	coarse structure resolution	near field, super-resolution, strong priors
$R + T + A = 1$	passive linear systems without gain	active media, frequency conversion, time-varying media
$I(X; Y_{\text{digital}}) \leq I(X; Y_{\text{analog}})$	pure post-processing	priors, training data, sensor fusion
$p(y \theta) = \text{Tr}(\rho_\theta E_y)$	standard form of outcome probabilities	not a complete interpretation of the measurement problem
$K = \text{SNR} \cdot C^2$	scalar Gaussian channel	any coupling of signal and noise
$K = \prod \kappa_i$	only where separability (10) holds; class A exact, B asymptotic	class C: multi-stage noise, aperture, nonlinearity, crossover regime
η_k stage-intrinsic	class A	once noise at the chain end dominates (14.6)
$\Phi_e = 2s/(1 + s^2)$	two counter-propagating components along one axis	multimode fields
$F_Q = e^{-2\Gamma t}$	qubit, pure dephasing, phase estimation	additional relaxation, multi-qubit systems

Appendix C — Reproduction

`cd werkzeuge`

```
python3 FORSCH-PROV0420_minimalmodelle_v0.2_2026-08-26_numerik.py # M1-M6, seed 20260826
python3 FORSCH-PROV0420_minimalmodelle_v0.3_2026-10-05_numerik.py # M7-M10, seed 20261005
```

Dependencies: Python 3, `numpy`, `matplotlib`. The scripts write `ergebnisse.json` and `ergebnisse_v0.3.json` and all figures to `werk/abb/`. Every number in Section 14 comes from these files.

Appendix D — References

Every entry carrying an identifier (DOI, ISBN, bibcode) was confirmed for this version with the publisher, the registration agency’s record, or the full text. Entries without an identifier are standard textbooks whose edition is still to be fixed; they are listed as open in Appendix I.

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Appendix E — Errata and version history

Version	Change
v0.1 → v0.2	K dimensioned and derived; separability criterion introduced; falsification case 3 tightened to LTI; notation decoupled ($\mu \rightarrow \gamma$, $s_e \rightarrow c_e$, $S_e \rightarrow \Phi_e$, $K_e \rightarrow K_\Phi$); Φ_e identified with VSWR; null space extended to the singular-value continuum; identifiability named; six numerical models; DOIs added; spelling Bertero & Boccacci corrected; bilingual DE+EN
v0.8 → v0.9	nothing in the work itself; the bundle made ready for publication: VEROEFFENTLICHUNG.md as the sequence in one place, landing page extended with legal matters and the network of brands, citation template in the author register raised from Version 0.3 to the current version
v0.7 → v0.8	new Appendix G.6: self-protection and the disclosure line per REGEL-PROV0002; for every component it is stated whether it is open and why; checkability outranks protection recorded as the precedence; the choice for the browser tool made and justified
v0.6 → v0.7	new Appendix G.5: active and passive versions per the cross-track rule REGEL-PROV0001; the borderline case of computation scripts settled in favour of checkability; the difference between free verification and the licensed tool stated
v0.5 → v0.6	commercial arrangement converted to a platform-centred one: Appendix G rewritten (syntagma-science as the destination, the open channel as the feeder), licence levels L0–L3 and six product classes per LIZ-PROV0001 added, Appendix H reordered to platform → deposit → journals, Zenodo bundle prepared separately; tools run exclusively on the platform
v0.4 → v0.5	source check carried out and folded in (verified entries 23 → 50, open 25 → 12): ISO 12233 corrected to the 2024 edition with its changed title; IEC TR 60825-14 dated to 2022 (Ed. 2.0) and the status of IEC 60825-1 Ed. 4 noted; the conference paper WSA 2010 replaces the arXiv preprint as the primary source for one-bit quantisation; journal name corrected for Kalman (1963) ; six missing DOIs added; issue numbers added for ten entries; Appendix D converted into one continuous alphabetical list; Appendix I structured into verified / still open / what the check changed; open entries reduced from 25 to 13
v0.3 → v0.4	gap claim tied to the strands searched; class C extended by three cases; noise coefficient and Stam inequality demarcated; Section 7.1 (Rayleigh and Sparrow as d' thresholds); convention for the excess noise factor fixed; quantum bounds under noise and QFI monotonicity added; Appendix H (publication path) and Appendix I (source checklist) new; twelve references added

Version	Change
v0.2 → v0.3	core statement identified as observational equivalence; Theorem 1 with proof; Theorem 2 (stage formulation); classification A/B/C; demarcation from Cox–Reid and DQE; four new minimal models M7–M10; experimental protocol; Vienna lineage; demarcation from observability theory; Appendices F and G new

Appendix F — What was not found in the literature

The following list belongs to the integrity of the contribution. It states what could not be found after reviewing the strands data-processing inequality, cascaded systems and detective quantum efficiency, quantisation, detector noise, parameter orthogonality, information geometry, observability theory and structural identifiability. The search comprised roughly two dozen targeted queries; it was not exhaustive and does not replace a systematic review. **“Not found” does not mean “does not exist”**. Every statement in this appendix is qualified accordingly in the text.

Sought	Status
General criterion $\partial^2 \log F / \partial p_i \partial p_j = 0$ for cascaded measurement chains	not found; the DQE literature explicitly denies the general product form
“Separable” or “multiplicative Fisher information” as a named concept	not found
Information geometry of the model family over the instrument-parameter space (fibre bundle)	not found
Existence theorem for a mixing reparametrisation making $\log F$ separable	not found
Teaching experiment with a radiometrically calibrated raw sensor and an estimate of Cramér–Rao efficiency	not found
Philosophical work explicitly treating gauge orbits as the null space of the Fisher metric	not found

Appendix G — Track assignment and commercial use

This work is run platform-centred. The platform **syntagma-science** is where everything converges; the open research channel feeds it rather than being the destination.

G.1 The two tracks

Track	Content	Licence	Location	Role
syntagma-science (platform)	the MESSWERK tool in two editions, documentation, training, measurement-chain audit, design work	licensed, levels L0–L3	syntagma-science/ , syntagma-science.com	Destination. Every tool runs here, this is where purchases and installations happen
FORSCHUNG / Syntagma Forschung	this preprint, figures, computation scripts, raw results	CC BY 4.0, open	werk/ , zenodo-upload/ , forschung.tschueller.com	Feeder. Substantiates the method openly and leads to the platform

Tools run exclusively on the platform. No tool is deposited on Zenodo, not even a preview or demonstration build — what is deposited there is the preprint with figures, scripts and raw results. Anyone who wants to compute rather than read comes to the platform.

G.2 Licence levels

Following the licence and platform scheme LIZ-PROV0001.

Level	What it covers	For this work
L0 — open	freely readable, CC BY 4.0, no registration	preprint in all four formats, both languages, nine figures, both computation scripts, both raw-result files
L1 — read	platform registration, bundle access, version tracking	curated reading view of the work with cross-references into the tool modules
L2 — apply	tool use, updates, support	MESSWERK universal, six computation modules, single seat or embedding
L3 — install	multi-seat, own branding, training, audit	MESSWERK white-label, measurement-chain audit, design against a required accuracy

G.3 Product classes

Class	Filled in this project by	Level
Preprint	the present work	L0
Monograph	not filled — an expanded book is conceivable but not begun	—
Tool Basic	MESSWERK universal, six browser modules	L2
Tool Pro	MESSWERK with own branding, multi-seat, data import from photon-transfer calibration	L3
Course	half-day training “measurability instead of signal strength”	L2/L3
Institutional licence	technical college, university of applied sciences, test laboratory: tool plus training plus audit	L3

G.4 What this means for publication

The open preprint is a publication and reach channel, not an end in itself: it substantiates the method openly so that the platform rests on something checkable. Every deposit of the preprint carries the reference to syntagma-science. Both tracks are maintained; neither replaces the other. The identifiers FORSCH-PROV0420 and SYN-PROV0002 are provisional and are to be checked against the register before publication.

G.5 Active and passive versions

The assignment follows the cross-track rule **REGEL-PROV0001** (version 1.0 of 6 Oct 2026, text in *regelwerk/*). It governs all projects, not only this one.

Only the passive version goes on the deposit. The active version runs exclusively on the platform.

	Active → platform only	Passive → deposit permitted
Mark	has an operating surface and computes, decides or produces in response to input	is read, viewed, or run once for verification

	Active → platform only	Passive → deposit permitted
In this project	MESSWERK in both editions, six browser computation modules	this work in four formats per language, nine figures, both computation scripts, both raw-result files

The test, in this order: does it have an operating surface that computes on input? If yes, active. If no: is it read, viewed, or run once for verification? If yes, passive.

The computation scripts of Appendix C are passive and go on the deposit. A fixed-seed script that regenerates the numbers of Section 14 is reproduction material, not an application. Without it this work could not be checked, and checkability is the reason for depositing at all. Anyone who wants to verify the numbers here does not need MESSWERK; the scripts suffice. MESSWERK removes the setup work and computes on someone else’s measurement chain rather than on the examples of this work — that is the difference the licence rests on.

Never on the deposit: preview, demonstration and reduced builds of the tool, the tool’s source including its surface, offering and pricing material, and internal files. Either the full tool on the platform or none at all.

G.6 Self-protection and the disclosure line

The line between what lies open and what stays with the author follows the cross-track rule **REGEL-PROV0002** (version 1.0 of 6 Oct 2026, text in `regelwerk/`). It is named here because this work sits beside a paid offering, and the question would otherwise go unstated.

The line runs at the subject, not the format: the method this work claims and substantiates is public. Without evidence it would be advertising, not research. The product sold alongside it is protected.

Subject	Status	Reason
Theorems 1 and 2 with proofs, classification A/B/C	open	this is the claim; publishing it without proof would be worthless
Computation scripts M1–M10 with fixed seeds	open	they regenerate every number of Section 14; without them the work cannot be checked
Experimental protocol, Section 19	open	it describes how to refute the theory , not how to build the product . It names component classes, not suppliers, and refers calibration to the public EMVA 1288 standard rather than to in-house correction tables
Own calibration data, correction tables, suppliers, part numbers	not present	under REGEL-PROV0002 these stay internal in any case; they are not needed here and appear nowhere
Prices, cost prices, costing	not present	price levels belong in the licence scheme LIZ-PROV0001, not in a preprint

Checkability outranks protection. Where a detail is needed to keep the claim refutable, it is published, even where a third party benefits. A framework that cannot be refuted supports no offering.

A browser tool, deliberately open. MESSWERK runs as a single HTML file in the browser and therefore ships its computing core to everyone who opens the page. “In the browser” and “core source internal” exclude each other; REGEL-PROV0002 accordingly requires a deliberate choice per tool. For MESSWERK the choice has been made and is recorded in `syntagma-science/ANGEBOT.md`: **the universal edition stays open on the platform page**. The licence then carries not the computing core but maintenance and version tracking, own branding and multi-seat operation, training, the measurement-chain audit and design against a required

accuracy. This is not a fallback but the decision to weigh the funnel higher than the protection of a few hundred lines of computation code that are derivable from this work anyway.

Appendix H — Publication path

H.1 Order

Platform first, deposit second, journals last.

Step	What	Why in this order
1	Set up syntagma-science: work page, MESSWERK in the universal edition, documentation, licence levels	the platform is the destination; every later reference has to point somewhere
2	Deposit the Zenodo bundle (zenodo-upload/) with a DOI, CC BY 4.0, and the reference to the platform in both the description and the work	secures priority and citability; carries readers onward
3	Submit the individual articles , each referring to the deposit	review takes time; priority is already secured by then

H.2 The Zenodo bundle is prepared separately

The working bundle and the publication bundle are not the same thing. The folder `zenodo-upload/` holds exactly what belongs on the deposit and nothing else: preprint in four formats per language, figures, computation scripts, raw results, licence, metadata record, read-me. It does not hold tool builds, offering and pricing material, internal handovers or checklists. The bundle’s metadata name the platform as the related identifier.

H.3 Journals and repositories

Venue	Fit	Requirements
syntagma-science.com	the destination	own platform, no external requirements; licence levels per Appendix G.2
Zenodo with ORCID	immediately possible, subordinate	no endorsement, DOI on request; suitable for the bilingual monograph; the description points to the platform
arXiv <code>physics.data-an</code> , cross-list <code>eess.SP</code> , <code>quant-ph</code> , <code>physics.hist-ph</code>	high, but with a hurdle	Endorsement required. Since 21 Jan 2026 automatic endorsement requires both an institutional e-mail address and a prior publication in the same endorsement domain. In physics each subject class is its own domain. Without both, a personal endorsement by an established arXiv author of the same domain is needed; operations staff cannot endorse open access; an article processing charge applies on acceptance (CHF 2600 per the publisher)
<i>Entropy</i>	high for the mathematical core	

Venue	Fit	Requirements
<i>Measurement Science and Technology</i> <i>Metrologia</i>	medium to high once the experiment exists medium	requires experimental validation only with a clear link to GUM and VIM
<i>European Journal of Physics</i> , <i>American Journal of Physics</i> <i>Synthese</i> , <i>Studies in History and Philosophy of Science</i>	high for the experimental part for the philosophical part	teaching-lab focus; Section 19 is already cut for this requires philosophical originality beyond the placement

H.4 Recommended split

A single work covering mathematics, experiment and philosophy of science fits no single journal. Splitting it into three submissions is more workable, with the bilingual monograph as the common, openly accessible deposit:

Article	Content	Target
1	Theorem 1, Theorem 2, classification A/B/C, models M1, M4, M7, M8	<i>Entropy</i> or a correspondence in an information-theory journal
2	experimental protocol, models M3 and M10, photon-transfer calibration	<i>European Journal of Physics</i>
3	Sections 16 and 17, expanded	<i>Synthese</i> or <i>Studies in History and Philosophy of Science</i>

Appendix I — Source checklist

Status **verified** means the entry was confirmed for this version against the publisher’s record, the standards register, the full text, or the registration agency’s entry. **open** means the entry is still not individually substantiated and is to be confirmed before a journal version. The check was carried out on 6 Oct 2026.

I.1 Verified

Source	Identifier	Evidence
Rothenberg (1971)	DOI 10.2307/1913267	publisher
Cox & Reid (1987)	DOI 10.1111/j.2517-6161.1987.tb01422.x	publisher
Zamir (1998)	DOI 10.1109/18.669301	publisher
Braunstein & Caves (1994)	DOI 10.1103/PhysRevLett.72.3439	publisher
Helstrom (1969)	DOI 10.1007/BF01007479	publisher
Kullback & Leibler (1951)	DOI 10.1214/aoms/1177729694	publisher
Morgenthaler (1958)	DOI 10.1109/TMTT.1958.1124533	publisher
Friis (1944)	DOI 10.1109/JRPROC.1944.232049	publisher
Rabbani, Shaw & Van Metter (1987)	DOI 10.1364/JOSAA.4.000895	publisher
Cunningham, Westmore & Fenster (1994)	DOI 10.1118/1.597401	publisher
Cunningham & Shaw (1999)	DOI 10.1364/JOSAA.16.000621	publisher — formed from the publisher’s pattern in v0.4, now confirmed
Robbins & Hadwen (2003)	DOI 10.1109/TED.2003.813462	publisher
Hynecek & Nishiwaki (2003)	DOI 10.1109/TED.2002.806962	publisher
Chao, Ward & Ober (2012)	DOI 10.1007/s11045-011-0150-7	publisher

Source	Identifier	Evidence
Mortensen et al. (2010)	DOI 10.1038/nmeth.1447	publisher
Escher et al. (2011)	DOI 10.1038/nphys1958	publisher
Raue et al. (2009)	DOI 10.1093/bioinformatics/btp358	publisher
Hermann & Krener (1977)	DOI 10.1109/TAC.1977.1101601	publisher
Krener & Ide (2009)	DOI 10.1109/CDC.2009.5400067	publisher — listed as missing in v0.4
Quine (1951)	DOI 10.2307/2181906	publisher
Zurek (2003)	DOI 10.1103/RevModPhys.75.715	publisher
Schrödinger (1935), Parts I and II	DOI 10.1007/BF01491891, 10.1007/BF01491914	publisher
Gan & Law (2009)	DOI 10.1088/0143-0807/30/6/006	publisher
Aspden, Padgett & Spalding (2016)	DOI 10.1119/1.4955173	publisher
Bertero & Boccacci (1998)	ISBN 978-0-7503-0435-1	publisher (spelling Boccacci)
Chernoff (1952)	DOI 10.1214/aoms/1177729330	publisher
Amari (2001)	DOI 10.1109/18.930911	publisher
Amari (2016)	DOI 10.1007/978-4-431-55978-8	publisher
Paris (2009)	DOI 10.1142/S0219749909004839; issue 7(Suppl. 1) added	publisher
Hughston, Jozsa & Wootters (1993)	DOI 10.1016/0375-9601(93)90880-9	publisher
Kalman (1963)	DOI 10.1137/0301010; journal name corrected to <i>J. Soc. Ind. Appl. Math., Series A: Control</i>	publisher
Bellman & Åström (1970)	DOI 10.1016/0025-5564(70)90132-X; issue 7(3–4) added	publisher
Worrall (1989)	DOI 10.1111/j.1746- 8361.1989.tb00933.x	publisher
Earman & Norton (1987)	DOI 10.1093/bjps/38.4.515	publisher
Carnap (1936/37)	DOI 10.1086/286432 and 10.1086/286443	publisher
Mezghani, Antreich & Nossek (2010)	DOI 10.1109/WSA.2010.5456454; WSA 2010, Bremen, 143–150	publisher — the conference paper is now the primary source, arXiv:1010.5532 the preprint
Galiffi et al. (2022)	DOI 10.1117/1.AP.4.1.014002	publisher — no DOI in v0.4
Hansen (1998)	DOI 10.1137/1.9780898719697	publisher — no DOI in v0.4
Janesick (2007)	DOI 10.1117/3.725073	publisher — ISBN only and unverified in v0.4
Stadler (2015)	DOI 10.1007/978-3-319-16561-5	publisher — ISBN only and unverified in v0.4
Landauer (1991)	DOI 10.1063/1.881299; issue 44(5)	publisher
Shannon (1948)	DOI 10.1002/j.1538- 7305.1948.tb01338.x and 10.1002/j.1538- 7305.1948.tb00917.x; issues 27(3) and 27(4)	publisher
Berreman (1972)	DOI 10.1364/JOSA.62.000502; issue 62(4)	publisher
Hempel (1950)	<i>Revue Internationale de Philosophie</i> 4(11), 41–63	full-text evidence via the collective review in the <i>Journal of Symbolic Logic</i>
Trimmer (1980)	JSTOR 986572	publisher — no DOI has been assigned
Sparrow (1916)	bibcode 1916ApJ....44...76S	full text in the ADS archive
Rayleigh (1879)	DOI 10.1080/14786447908639684	publisher

Source	Identifier	Evidence
ISO 12233:2024	standard, 5th edition	ISO register — replaces ISO 12233:2023 ; the title also changed : “Digital cameras — Resolution and spatial frequency responses” instead of “Photography — Electronic still picture imaging — ...”
IEC TR 60825-14:2022 (Ed. 2.0)	standard	IEC register
IEC 60825-1:2014 Ed. 3.0 + AMD1/AMD2:2017; EN 60825-1:2014 + A11:2021	standard	IEC register — a 4th edition stands at stage 30.60 (close of voting 2 Oct 2026) and is not published

I.2 Still open

Source	Identifier	Status
Abbe (1873)	<i>Arch. mikrosk. Anat.</i> 9(1), 413–468	open — issue and page range from the secondary literature; no DOI on record
Schrödinger (1935), Part III	—	open — no DOI is on record for the third part
Goodman, <i>Introduction to Fourier Optics</i>	edition and ISBN	open — the edition is to be fixed before the journal version
Kay (1993)	ISBN	open
Green & Swets (1966)	ISBN	open
Krantz et al. (1971)	ISBN of the reprint	open
Tikhonov & Arsenin (1977)	ISBN	open
Born & Wolf; Boyd; Cover & Thomas; Jackson; Mandel & Wolf; Nielsen & Chuang; Pozar; Van Trees; Woodward	edition and ISBN	open — standard textbooks with no edition-bound passage cited in this work
Boltzmann (1905), Mach (1886), Bridgman (1927)	first editions	open — edition not checked against a copy
JCGM 100:2008, JCGM 200:2012	BIPM	open — edition status not checked against the document
EMVA 1288 Release 4.0	standard	open — valid module designation not checked against the standard text
Tal, <i>Measurement in Science</i> (SEP)	version date	open — the SEP is revised continuously; an access date is to be added

I.3 What the check changed in the work

Item	v0.4	v0.5
Standard for the MTF measurement	ISO 12233:2023	ISO 12233:2024 , 5th edition, with a changed title
Laser safety guidance	IEC TR 60825-14 without a year	IEC TR 60825-14:2022 , Ed. 2.0
One-bit quantisation	arXiv preprint as the source	conference paper WSA 2010 with a DOI as the primary source
Kalman (1963)	<i>SIAM Journal on Control</i>	J. Soc. Ind. Appl. Math., Series A: Control — the present journal name is the later one

Item	v0.4	v0.5
open entries	25	12, almost exclusively edition and ISBN questions
verified entries	23	50