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Thermodynamical Theories Survey and Comparison

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Each survey of a field is based on a subjective choice and valuation of the subject which can not be undertaken without any arbitrariness. Beyond that a most detailed representation of all numerous thermodynamics theories should not be given here in favour of getting an easier structure. Therefore some representative facts of thermodynamical theories should be discussed vicariously for all that can not be mentioned here without achieving completeness, e. g. variational principles of thermodynamics are not discussed ^[1,2,30]. Starting out with some well known facts, we will deal with disciplines chosen as representatives in the order of their historical development:

Thermostatistics

Linear irreversible thermodynamics

Non-Classical thermodynamics

Theories with evolution criteria.

In the field of heat theories of macroscopic systems we distinguish between totally different proceedings which are supplementing each other: phenomenological and statistical theories (Fig. 1). The first ones do not take into consideration the molecular structure of materials whereas statistical theories embrace this structure by microscopical models using master equations or representative ensembles^[3].

Here we restrict ourselves on discussing exclusively phenomenological non-equilibrium thermodynamics. The basic concept of phenomenological theories is that of the macroscopic variable. These quantities are parameters of the state of the system which can be retraced immediately or mediately to measuring quantities of the system. Examples are volume, pressure, temperature, mass density, charge density, magnetization, pressure tensor, internal energy etc.

In the following we will shortly motivate why there exist a lot of similar thermodynamical theories which are in principle different in their interpretations. The transition from mechanics to thermostatistics is achieved by adding thermodynamical quantities to the mechanical ones. Besides other quantities especially

Theories of macroscopic systems taking into account their agitation by heat							
taking into account their molecular structure							
without					with		
phenomenological theories					statistical theories		
non-equilibrium thermodynamics					kinetics	statistical physics	
macroscopic variables					master equations	representative ensembles	
thermo- statics	classical irrever- sible thermody- namics	rational thermody- namics	non-classi- cal thermody- namics	evolution criteria	transport theories	equili- brium	non- equi- libri- um

Fig. 1 Scheme representing the relationship between phenomenological theories and statistical ones

state space	{ small large
temperature entropy	{ primitive concept derived quantity
dissipation inequality	{ local in time global in time
relation $q \leftrightarrow \phi$	{ universal material dependent

Fig. 2 Catagories for classifying phenomenological thermodynamical theories

temperature and entropy are added. Because both these quantities are defined by measuring rules in equilibrium, the transition from mechanics to thermostatics has no problematic nature. Because temperature and entropy are to be used also in non-equilibrium, the question arises how to define them in non-equilibrium. This question can be answered differently in principle, and therefore no natural extension of thermostatics to thermodynamics exists^[4]. Either temperature and entropy will be redefined for non-equilibrium or they are taken for primitive concepts, i.e. their mathematical existence is presupposed and first of all a physical verification remains open (Fig. 2).

Besides the problem of introducing temperature and entropy in non-equilibrium other possibilities of generalisation appear by transposing thermostatics into thermodynamics. So the used state spaces may be based on different definitions of state, the dissipation inequality may be local or global in time, and the relation between heat flux density q and entropy flux density ϕ may be universal or dependent on material (Fig. 2).

1. State Space

The phenomenological description of systems needs state spaces z which are at least Hausdorff spaces because of the physical measuring instruments. Trajectories in such a state space

$$P: [i, f] \subset R^1 \rightarrow Z(\cdot) \subset z; t \in R^1 \mapsto Z(t) \in z \quad (1-1)$$

are representing processes which the system undergoes. There now exist two kinds of state spaces which are called large and small ones and in which material properties \mathbb{M} are represented differently:

Definition: A state space z is called large, if material properties \mathbb{M} are defined by maps being local in time

$$\mathbb{M}: z \rightarrow \mathfrak{M} \text{ Hausdorffian, } Z(t) \mapsto M(t), \text{ for all } t. \quad (1-2)$$

A large state space contains by definition so many variables so that all material properties at time t are determined by the state variable $Z(t)$ at the same time t . Such “comfortable” state spaces are existing for thermoelastic material^[5] or in thermostatics^[6]. In general, however, not all variables are known which span large state spaces, and therefore material properties become dependent on the history of state variables.

Definition: For a fixed time t , real $s \geq 0$, and with

$$Z^t(s) := Z(t-s), t-s \in [i, f], Z^t(\cdot) \subset z, Z^t(\cdot) \in z^t(\cdot), \quad (1-3)$$

is called history of the process $Z(\cdot)$ up to time t .

Therefore the history of a process is defined as that part of a process trajectory which is coming from past reaching up to time t .

Definition: A state space is called small, if material properties \mathbb{M} are defined by maps on process histories which therefore are not local in time

$$\mathbb{M}: z^t(\cdot) \rightarrow \mathfrak{M}, Z^t(\cdot) \mapsto M(t), \text{ for all } t. \quad (1-4)$$

Therefore by definition all state spaces are small for materials showing after-effects.

2. Second Law

Further differences between thermodynamical theories arise by the formulation of the Second Law. Because there is no natural extension of the equilibrium entropy to non-equilibrium^[7], it was said that there are as many formulations of the Second Law as there are authors^[8]. Despite of such manifold of formulations they can all be divided into in time local ones and into in time global ones. Here the global formulations are related to path integrals along process trajectories. Because the usual verbal formulation of the Second Law (there are no Kelvin processes) is

also global in time, it was preferred to formulations being local in time (the entropy production density is not negative). It is unjustified to do so because we know an existence theorem for non-negative in time local entropy productions^[9,37].

3. Relation between Entropy and Heat Flux Density

The field of the entropy flux density ϕ appears in the balance of entropy. For systems of one component it depends on the heat flux density q homogeneously and locally

$$\phi(x, t) = A(\dots)q(x, t). \quad (3-1)$$

Thermodynamical theories are now distinguished by the coldness^[10] being universal or dependent on material properties.

4. Thermostatistics

For repetition we put together the facts of thermostatistics: The state space of thermostatistics is axiomatically fixed by the Zeroth Law. For thermal homogeneous systems it includes (Fig. 3)

- the work variables a
- the mole numbers n , and
- an additional thermal variable, the internal energy U or the thermostatical temperature T

Here T is defined by a division of equilibrium systems into classes of equivalence by thermal equilibrium^[11]. As T the entropy S is also no primitive concept in thermostatistics. Its differential is defined by Gibb's fundamental equation

$$T \, dS := dU - A \cdot da - \mu \cdot dn \quad (4-1)$$

(μ =chemical potentials). Using the First Law^[12]

Zeroth Law: state space $(a, n, *) = (\cdot) \in \mathbb{Z}$ a =work variables, $W=A \cdot a$ n =mole numbers, $*$ = U or T	
Thermostatic temperature T : thermostatic equilibrium generates a division into classes of equivalence defining T	
Thermostatic entropy S : $\dot{S} := \dot{Q}/T + s \cdot \dot{n}^e$	Clausius' inequality: $\oint (\dot{Q}/T) + s \cdot \dot{n}^e \, dt \leq 0$
State functions: $H(\cdot), F(\cdot), G(\cdot), S(\cdot)$	

Fig. 3 Thermostatistics (W =power, A =generalized forces)

$$dU = DQ + DW + \mathbf{h} \cdot d\mathbf{n}^e \quad (4-2)$$

(DQ =heat exchange, \mathbf{h} =molar enthalpies, $d\mathbf{n}^e$ =external rate of mole numbers) we get

$$dS = DQ/T + \mathbf{s} \cdot d\mathbf{n}^e \quad (4-3)$$

(\mathbf{s} =molar entropy). If we denote derivations along process trajectories by a dot, we get from (4-3) the rate of entropy mentioned in Fig. 3.

The dissipation inequality of thermostatics is Clausius' inequality which is global in time and holds for discrete non-equilibrium systems. Here T and \mathbf{s} are quantities which belong to the controlling equilibrium reservoirs and not to the system itself. The state space of thermostatics is a large one. The constitutive equations describing material properties are represented by state functions. Some historical hints are given in Fig. 4.

CARNOT	1824	cyclic processes
MAYER	1842	
JOULE	1843	First Law
HELMHOLTZ	1847	
THOMSON	1848	absolute temperature
CLAUSIUS	1850	
THOMSON	1851	Second Law
CARATHEODORY	1909	inaccessible axiom
BORN	1921	inaccessible axiom

Fig. 4 Some historical dates in connection with thermostatics

5. Classical Irreversible Thermodynamics

Classical irreversible thermodynamics is based on the postulate of local equilibrium (Fig. 5). If it holds, the variables of thermostatics are sufficient for a field formulation which is local in position and in time. Because in that case temperature and entropy are defined by thermostatics the balance equations of mass, momentum, energy, and entropy can be formulated without additional assumptions. Therefore the state space of irreversible thermodynamics is a large one just as that of thermostatics. The entropy flux density is universal and equal to the heat flux density over thermostatic temperature. The entropy production density is representable as a scalar product of so called forces and fluxes. It is presupposed as non-negative in the sense of a dissipation inequality being local in time^[13]. Besides the four classical irreversible phenomena, diffusion, heat conduction, internal friction and chemical reactions electromagnetic phenomena and polarized materials can also be included into irreversible thermodynamics. Of course in this theory the

Local equilibrium: $\mathbb{R}^4 \rightarrow \mathbb{Z}: (\alpha, n, *) (x, t)$
Balance equations: mass, momentum, energy, entropy: $\rho \dot{s} = -\nabla \cdot \phi + \sigma$
$\phi = q/T, \sigma = X \cdot Y \geq 0$, diffusion heat conduction internal friction chemical reactions
Constitutive equations: $Y = L \cdot X, X(-t) = \Lambda \cdot X(t)$ OCRR: $L(-B, -, \dots) = \Lambda \cdot L(B, \dots) \cdot \tilde{\Lambda}$

Fig. 5 Classical irreversible thermodynamics

constitutive equations are linearized and by using the state space of thermostatics propagation paradoxa then occur^[14]. The differential equations of diffusion and heat conductivity are parabolic, what can not be right because of physical reasons propagation velocities should be finite. The coefficients of the linearized constitutive equations satisfy the Onsager-Casimir reciprocal relations (OCRR, Fig. 5). These relations are restrictions beyond the Second Law following from symmetry under time reversal^[15,36]. Such restrictions of the constitutive equations are not to be found in other disciplines of non-equilibrium thermodynamics up to now. This fact produced a lively discussion about the meaning of OCRR^[16]. Some historical dates with respect to classical irreversible thermodynamics are given in Fig. 6 (N=Nobel prize winner).

	THOMSON	1854	thermo-electric phenomena
	De DONDER	1927	affinity
(N 1968)	ONSAGER	1931	reciprocity relations
	MEIXNER	1943	processes in chemical reacting media
	CASIMIR	1945	reciprocity relations
(N 1977)	PRIGOGINE	1947	textbook
		1951	helium II
	De GROOT	1952	textbook

Fig. 6 Some historical dates in connection with classical irreversible thermodynamics (N=Nobel prize winner)

6. Rational Thermodynamics

Historical rational thermodynamics is the thermal extension of rational mechanics. Although manifold some representative prototypes of rational thermodynamics can be specified^[8] (Fig. 7).

First of all we will discuss Clausius-Duhem theories which all use in time local Clausius-Duhem dissipation inequalities (CDI, Fig. 8) as analytical expression for describing the Second Law. Here entropy density and temperature Θ are primitive concepts, i. e. both the quantities are not defined physically.

Three of the chosen sets of theories are local in position, Truesdell et al. [16~19], and Mueller

et al. [5,38], two others are global in position, Green et al. [20], and Eringen [21]. Here the non-localities are different in a characteristic manner: Whereas Green et al. use the balance equations only in an integral from being valid for sufficiently small but not arbitrarily small domains. Eringen modifies the balance equations by so called residual which integrated over sufficiently large domains that do not contribute to the integral balance equations. On the contrary to the three other

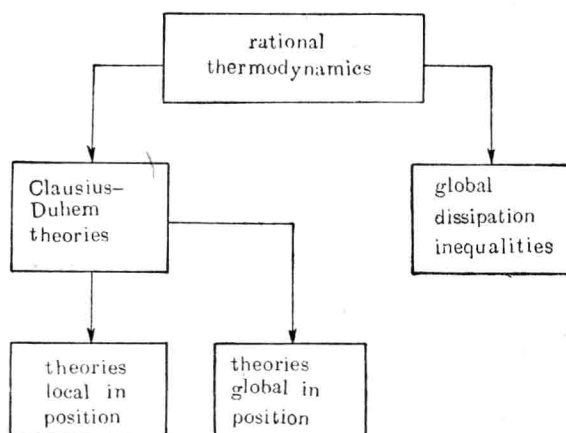


Fig. 7 Scheme how rational thermodynamics can be divided into

	Truesdell Coleman Noll 1973	I. Mueller 1971	I. S. Liu I. Mueller 1983	A. E. Green Naghdi 1972	Eringen 1972
ϕ	$k=0$	$\Lambda(v, \dot{v})q$	$k=\alpha\dot{P}\cdot q$ $\alpha=-(2/5)f$ $f=T^{-(7/2)}F$ $F=g(\rho T^{-(3/2)})$	$k\neq 0$	$k=0$
γ	$\rho(r/\Theta)$	$\lambda\cdot f+\lambda r$	0	$\rho(r/\Theta)-\rho\mu$	$\rho(r/\Theta)+\rho\hat{s}+\hat{\rho}s$
state space	small	large	large	small	small
local in position	+	+	+	$\int \rho\mu dV=0$	$\int \rho\hat{s} dV=0$
balance equations as constraints	-	+	+	-	-

Fig. 8 Clausius-Duhem theories presuppose the existence of CDI: $\rho\dot{s}+\nabla\cdot\phi-\gamma=\sigma\geq 0$, $\phi=q/\Theta+k$. Entropy density and temperature are considered as primitive concepts (σ =entropy production density, γ =entropy supply, r =heat supply, \dot{P} =traceless part of pressure tensor)

theories Mueller et al. use large state spaces. Therefore the entropy density and the entropy production density are state functions, and in these theories analogues exist to Maxwell's relations of thermostatics.

A further characteristic difference exists in exploiting the dissipation inequality which in Clausius-Duhem theories is considered as restriction for constitutive equations. Usually those material functions (1-4) are not allowed which for arbitrary processes (1-1)-i. e. without taking into consideration the balance equations do not satisfy the dissipation inequality. On the contrary Mueller et al. do take into consideration the balance equations as restriction for exploiting the dissipation inequality. He only separates those constitutive equations which do not satisfy the dissipation inequality but belong to real processes, i. e. which are solutions of the balance equations.

The relation between ϕ and q is universal in theories with $k=0$ whereas in those with $k \neq 0$ it may be dependent on material properties. The coldness^[10] $A(v, \dot{v})$ (v =empirical temperature physically not defined) is taken for universal. This is doubtful because of its dependence on \dot{v} and can not be confirmed for multi-component systems^[22].

Extended thermodynamics is a Clausius-Duhem theory being local in position and using large state spaces. The difference compared with the 1971-theory is the choice of the state space. Whereas the 1971-theory is a 5-field theory in the easiest case-mass density, velocity or momentum density, and temperature or energy density span the state space-extended thermodynamics uses a 13-dimensional state space: mass density, velocity, momentum flux density, and energy flux density. The usual balance equations of mass, momentum and energy which determine the state space in the 1971-theory, are replaced in extended thermodynamics by 13 balance equations which belong to the 13 quantities spanning the state space. In extended thermodynamics as well as in the 1971-theory the state space is determined by the balance equations under consideration. This is of course a formal procedure because constitutive equations describing material properties may be defined on other state spaces which are not induced by the balance equations. As the 1971-theory extended thermodynamics uses the balance equations as constraints exploiting the dissipation inequality. Rational theories using dissipation inequalities being global in time also stick to the shortcoming that temperature is considered as a primitive concept. The only exception is Clausius' inequality because here temperature and entropy belong to the reservoirs controlling the process, and therefore they are well defined. Meixner^[23], Day^[24], Coleman et al.^[19] are using Θ as a primitive field quantity (Fig. 9).

In these dissipation inequalities no non-equilibrium entropy appears. Meixner

Classical thermostatistics	$\oint [(\dot{Q}/T) + \mathbf{s} \cdot \mathbf{n}^e] dt \leq 0$
MEIXNER 1969	$\int_A^B [s^e q + (1/\rho) \nabla \cdot (\mathbf{q}/\Theta)] dt \geq 0$
DAY 1972 COLEMAN, OWEN 1974	$\oint [(1/\rho) \nabla \cdot (\mathbf{q}/\Theta) - r/\Theta] dt \geq 0$

Fig. 9 Dissipation inequalities being global in time

uses an equilibrium entropy which can be interpreted as entropy of an accompanying process^[25]. This concept originates from non-classical thermodynamics which we deal with in the next section. Finally we refer to a paper by Bataille and Kestin^[39] in which rational thermodynamics is interpreted physically.

7. Non-Classical Thermodynamics

Non-classical thermodynamics is characterized by a dynamical concept of temperature. A non-equilibrium temperature is defined operationally by a dynamical measuring rule. Typical of the predecessors of non-classical thermodynamics is the equal use of different concepts of temperature. So Gurtin et al.^[30] use beside the field temperature Θ a surface temperature τ which is different from Θ (Fig. 10). Meixner^[23] introduces beside the field temperature T the thermostatic temperature T_{eq} of the accompanying U -projection^[9, 27] which is generated by a special projection of the non-equilibrium trajectory (1-1) onto the equilibrium sub-space. The dynamical measuring rule for a non-equilibrium temperature called contact temperature Θ is defined by a thermal contact between two discrete systems one of them being a non-equilibrium system the other an equilibrium system^[28, 29]. For fixed state of the non-equilibrium system the direction of the heat exchange \dot{Q} depends on the thermostatic temperature T of the equilibrium system (Fig. 10). There exists one and only one temperature T_2 of the equilibrium system [so that \dot{Q} vanishes with change of sign. This temperature $\Theta = T_2$ is called the contact temperature of the non-equilibrium system at a certain non-equilibrium state. Of course the contact temperature depends on the state of the non-equilibrium system as well as on the structure of the thermal contact^[40]. Other contact quantities such as pressure tensor and chemical potentials can be defined analogously^[41].

A field formulation can be achieved for the contact temperature which is only defined for discrete systems^[30]. An extension of Clausius' inequality by using contact temperature is possible^[31, 42]. The relation between entropy flux density and heat flux density depends on material properties.

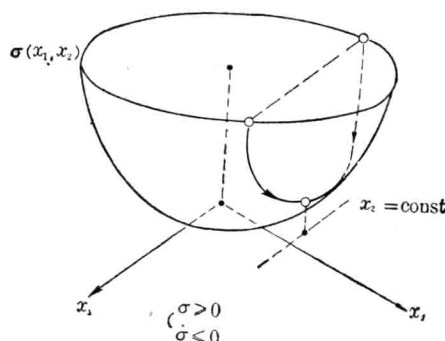


Fig. 12 Entropy production surface in the state space as Liapunow stability function

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热力学理论新的分类方法

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提 要

本文在对唯象非平衡热力学理论进行比较的基础上作了新的分类。该分类方法是以状态空间、温度和熵的概念、耗散不等式(dissipation inequality)及热流密度和熵流密度的关系等的不同形式作为区分各种理论的标准。文章采用了非平衡温度和熵的概念,对包括静态热力学、线性不可逆热力学和非经典热力学在内的所有唯象热力学理论作了分类。并在讨论具有局域(Local)耗散不等式的连续场系统热力学理论的同时,还对具有整体(global)耗散不等式的分立系统热力学理论进行了论述。

多普勒导航雷达低高度性能分析与计算

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(上海交通大学)

提 要

本文共分两部分。第一部分分析了调频连续波多普勒导航雷达存在低高度限制的原因。证明了取 J_1 一阶边带时, 调频连续波多普勒雷达可以工作到零高度, 否则存在低高度限制, 并推导出其最小起量高度的计算方法。第二部分着重分析了脉冲体制多普勒雷达存在低高度限制的原因。推导出最小起量高度的简捷而实用的计算方法, 用此方法计算了 AN-APN220C 多普勒雷达的最小起量高度。其计算结果与美国瑞安公司的实测值相符合。

一、调频连续波多普勒导航雷达低高度性能

1. 调频连续波多普勒雷达存在低高度限制的原因

在调频连续波多普勒雷达中, 从接收机取出的差频有用信号各阶边带分量 J_n 是宗量 M_f 的第一类贝塞尔函数:

$$J_n(M_f) = J_n\left(2m_f \sin \frac{\Omega_m \tau}{2}\right)$$

式中 Ω_m 是调制信号的角频率, $\Omega_m = 2\pi F_m$; $m_f = \frac{\Delta f}{F_m}$ 为调制系数, Δf 为最大频偏; $\tau = 2r/c$ 为地面回波时延。

飞机在低高度飞行时, $M_f = 2m_f \sin \Omega_m \tau / 2$ 很小或等于零, 对第一类贝塞尔函数, 下列近似式成立:

$$J_0(M_f) \approx 1; \quad J_1(M_f) \approx \frac{1}{2} M_f; \quad J_n(M_f) \approx 0; \quad n \geq 2.$$

接收到的信号不足以使多普勒导航雷达正常工作, 因此, 调频连续波多普勒雷达存在低高度限制。

2. 选用 J_1 边带时, 调频连续波多普勒雷达可以工作到零高度

$$J_1(M_f) = \frac{M_f}{2} \left(1 - \frac{M_f^2}{2 \cdot 2^2} + \frac{M_f^4}{2 \cdot 2^4 \cdot 3!} - \dots\right)$$

式中
$$M_f = 2m_f \sin \frac{\Omega_m \tau}{2} = 2m_f \sin \Omega_m r / c.$$

在低高度工作时, $\sin \frac{\Omega_m r}{c} \approx \Omega_m r / c$, 这时 $M_f = 2m_f \frac{\Omega_m r}{c} = k_1 \cdot r$. 式中 $k_1 = 2m_f \Omega_m / c$

为一不随高度变化的常数。将 M_t 式代入 $J_1(M_t)$ 式,并考虑到低高度时 $M_t = k_1 \cdot r < 1$, 得出:

$$J_1(M_t) \approx \frac{M_t}{2} = \frac{1}{2} k_1 r = k_2 r$$

$J_1(M_t)$ 和有用信号的幅度成正比, 所以其功率利用系数 η_w 和 $J_1^2(M_t) = k_2^2 r^2 = k_3 r^2$ 成正比, 即 $\eta_w = k_3 r^2$ 。

另一方面, 可以证明, 在多普勒雷达中由于它的反射面是无限延伸的大地平面, 因此它的信噪比和距离平方成反比, 与功率利用率成正比, 即

$$S/N = k_4 \cdot \frac{1}{r^2} \eta_w = k_4 \cdot \frac{1}{r^2} \cdot k_3 \cdot r^2 = k_4 \cdot k_3 = k$$

这就证明了采用一阶边带时, 在上述近似条件得到满足的高度上, 雷达信噪比恒定不变。这是因为雷达信号在反射过程中其功率值随距离的平方成反比而下降, 但在采用一阶边带时其功率利用系数随距离的平方成正比而增加。所以在一定的高度范围内, 二者正好相互抵消。

3. 如果选用 J_1 以外的边带时, 调频连续波多普勒雷达不能工作到零高度。其最小起量高度计算方法如下

调频连续波多普勒雷达在最低工作高度 H_{\min} 工作时, 接到的信号功率比它在最大工作高度 H_{\max} 时接收到的信号功率增加 $(H_{\max}/H_{\min})^2$ 倍。其功率利用率和 $J_n^2(M_t)$ 成比例, 其中 M_t 随工作高度的降低而降低。如果 $(H_{\max}/H_{\min})^2$ 大于或等于 $(J_{n_{\text{高}}}/J_{n_{\text{低}}})^2$, 则雷达可以工作在 H_{\min} 上。

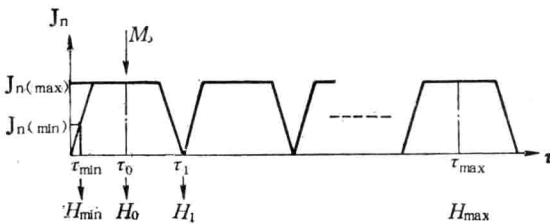


图1 贝塞尔函数值随信号延迟时间关系图

图1为任何一阶贝塞尔函数值随信号延迟时间变化关系图。

由分析得出, 第一个高度空穴对应的高度 $H_1 = \frac{c}{2F_m \sec \phi}$; 从图1可知 $H_0 = H_1/2$, H_0 高度对应的 $M_{t_0} = 2m_f \sin \frac{\Omega_m H_0}{c \cdot \cos \phi}$, H_0 对应的 $J_n(M_t)_0$ 为

$$J_n(M_t)_0 = \frac{M_{t_0}^n}{2^n n!} \left(1 - \frac{M_{t_0}^2}{2^n (n+1)} + \dots \right)$$

因为 J_n 是随 τ 周期性变化的, 所以 H_{\max} 处的 $J_n(M_t)_{\max}$ 和 H_0 处的 $J_n(M_t)$ 同样大小。最小起量高度 H_{\min} 对应的调制指数

$$M_{t_{\min}} = 2m_f \sin \frac{\Omega_m H_{\min}}{c \cdot \cos \phi}, J_n(M_t)_{\min} = \frac{M_{t_{\min}}^n}{2^n n!}$$

回波信号功率增加倍数 $(H_{\max}/H_{\min})^2$, n 阶边带功率利用率减小 $(J_{n_{\max}}/J_{n_{\min}})^2$ 倍。当

$$\left(\frac{H_{\max}}{H_{\min}} \right)^2 \geq \left(\frac{J_{n_{\max}}}{J_{n_{\min}}} \right)^2$$

时, 雷达可以工作在最小高度 H_{\min} 上。