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Power Transfer from Natural Emitters to Collecting Apertures at Microwave Wavelengths

J.M. Stacey

December 1, 1984

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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The mathematical relationships show explicitly and in closed form the expressions for signal-to-noise ratio as a function of certain key parameters.

An example is given for the practical case of an emitting object on the Earth and a collecting aperture in orbit.

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ABSTRACT

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The goal of the analyses is to show the power transfer criteria necessary and sufficient to produce a detection of the emitting object by the collecting aperture and its receiver.

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An example is given for the practical case of an emitting object on the Earth and a collecting aperture in orbit.

BACKGROUND

This monograph is concerned with the transfer of radiated power (radiant emittance, W_{obj}) from a passive, diffuse, emitting surface over an intervening range R_S that separates the emitting surface from a collecting aperture. The radiated power from the emitting surface, its propagation through space, and the collecting aperture that extracts the intercepted power from the arriving wavefront, are keyed to the properties of the microwave region.

The transfer of radiated power is modeled for the case of an emitting surface whose physical structure lies on or near the surface of the Earth and where a collecting aperture A_c is disposed in orbit at slant range R_s.

The goal of the analyses is to show the power transfer criteria that are necessary and sufficient to produce a detection of the emitting surface by the collecting aperture and the receiver to which it is connected.

The power transfer model is keyed to the practical case of an articulating (scanning) collecting-aperture which when configured as an antenna is known to possess a directional diagram which exhibits sidelobes that variably view the features of the Earth's surface in any arbitrary manner.

Intrinsic to the properties of the principal response is the specification that it contains an axis (ray) of maximum gain G_{max} and that this axis also passes through the phase center of the antenna feed and that its extension intercepts the emitting surface on the Earth during detection (Fig. 1).

The magnitude of the power transferred from the emitter to the collecting aperture is, in itself, insufficient to express the detection capability of the receiving system. Other factors that importantly influence the viability of a detection include the magnitude of the clutter residues that arrive at the input terminals of the receiver through the principal lobe and through the sidelobes of the antenna pattern. Ever present is the noise level of the receiver itself which systematically combines with the clutter elements to produce a combined noise level that competes with the signal power in the detection process.

The criterion which best expresses the expectation of detection is given by the ratio of the signal power P_S to the competing noise power P_N.

Signal power P_S is defined as the magnitude of the emitter irradiance that ultimately arrives at the terminals of the feed after it has suffered the propagation losses during the transit of the slant range and has been affected by the efficiency losses of the collecting aperture.

The noise power P_N is expressed by the orthogonal average (root sum of squares, RSS) of all the clutter and receiver noise elements that arrive at the terminals of the feed.

To conform with more conventional terminology, we redefine the ratio of P_S/P_N as the signal-to-noise ratio S/N of the receiving system. From the S/N and the predetection bandwidth of the receiver B, the information content, or the channel capacity of the measurement, may be derived. (C. E. Shannon, IEEE, Jan., 1949.)

By expectation, an articulating collecting aperture, which is principally concerned with detection of the radiant emittances from surface objects, must also suffer the effects of the interfering noise power levels arriving through the sidelobes and the principal lobe of the collecting aperture. These noise elements are called ground clutter.

The stochastic properties of clutter elements closely resemble those of normal receiver noise and frequently they are indistinguishable. For this reason, an orthogonal average of the clutter and the receiver noise elements is justifiable...even though in theory they may be resolved separately by sophisticated statistical processes.

Clutter irradiances arise, especially while scanning, from thermal discontinuities among land, forest, ice, and water features on the Earth. Clutter irradiances can be recast to be expressed as noise temperatures and to be consistent with the noise temperatures (temperature resolution, T_{res}) that express the sensitivity of a receiver.

Clutter temperatures, and the temperature resolution (frequently called "Delta Tee"), are consistently referred to the terminals of the feed and their individual root sum of squares may be calculated to express P_N for computing P_S/P_N in (S/N).

THE POWER TRANSFER RELATIONSHIPS

The geometry from which the power transfer equations are derived is illustrated in Fig. 1.

Central to the detection consideration is the emitting object which is identified as a Lambertian Disk Emitter.

The mathematical process and rationale that follow are keyed to the transfer of power from the emitting object to the collecting aperture, and finally to the terminals of the feed where the power from the emitting object and all competing noise components (clutter and receiver noise) combine for a single estimate of the S/N.

The S/N determines the detectability of the object and carries important inferences about the physical and thermal structure of the object itself.

Of equal importance to the transfer of power from the emitting object to the collecting aperture are the clutter components that ultimately arrive through the sidelobes and mainlobes of the directional diagram of the collecting aperture to the feed terminals. The clutter components are typically of greater magnitude than the receiver noise and for this reason dominate the N term of S/N.

The physical processes that generate clutter components, on and near the axis of maximum gain G_{max}, include the variable emissions from atmospheric constituents and the radiant emittances from the surface itself. Notably, both the upwelling and the downwelling paths of the G_{max} axis contribute, in a matter of degree, to the clutter variations and their magnitudes.

It is also apparent that with an articulating collecting aperture, the magnitude and character of the clutter, both on the G_{max} axis and in the multiple paths through the sidelobes, change from instant to instant, or from scan position to scan position of the articulating aperture.

Because the clutter arrives at the feed terminals through a variety of paths, and is affected by different concentrations of atmospheric particulates and surface effects, it is infeasible to separate them. Fortunately, it is not necessary that they be separable because all clutter effects are measurable and accountable as clutter components as they are received, and are assigned values on the clutter hyperplane (scan position matrix) which is produced by the scanning pattern of the collecting aperture.

The entries of the hyperplane also contain the power component transferred from the emitting object. Clutter noise and the transferred signal power component combine at the output terminals of the feed where they are thereafter reported as a single numerical quantity at the output of the receiver.

The unprocessed data appearing at the receiver output are defined as its primitive output. The primitive output data are dimensioned in relative number units called "digital counts."

The clutter hyperplane also contains the receiver noise component. The RMS value of the receiver noise is known precisely by benefit of a previous measurement.

The standard error of estimate of the clutter hyperplane precisely defines the variable (statistical) component of the clutter and receiver noise magnitudes with which the transferred power from the emittin object must compete in the resolution of S/N.

Clutter components that arrive through or near the G_{max} axis and those that arrive through the sidelobes are fundamentally noise power levels. Similarly, the internal noises generated by the receiver and referred to the output terminals of the feed, are power levels. It is reasonable therefore to express the total noise power P_N by

$$P_N = k\,T', \quad \text{watts/hertz} \tag{1}$$

where

$$T' = (T_{clut}^2 + T_{res}^2)^{1/2}, \text{ K}$$

k = 1.380662E-23, joules/kelvin, Boltzmann Constant

T_{clut} = Temperature of the clutter components, K

T_{res} = RMS noise temperature of the receiver ("Delta Tee") as referred to the terminals of the feed, K

Conforming to widespread usage and convention, it is convenient to express the temperature of the emitting object, the clutter components, and the temperature resolution of the receiver all in consistent units, namely kelvins. A more important reason, however, is because the radiant emittance from the emitting object is specified by its area and disk temperature difference with respect to its background temperature T_B (see Fig. 1.)

Disk area and disk temperature, as parameters, are key quantities that characterize the properties of the emitting object. One parameter value can be traded for the other to maintain a constant radiant emittance.

A successful detection or measurement of the emitting object is highly dependent upon its difference temperature T with respect to the background temperature T_B.

The intrinsic temperature of the emitting object T_{obj} is regarded as a diffuse, uniform, graybody emitter whose geometry is a disk. The disk figure is adopted because its area and dimensions are familiar and are easily converted into other geometrical figures as the occasion may require.

The emitting object is viewed by the phase center of the feed as a disk of uniform temperature T_{obj} that is superposed upon a background temperature T_B when the G_{max} axis of the collecting aperture is extended to intercept the center of the disk. The difference temperature T as expressed by

$$T = \left| T_{obj} - T_B \right|, \text{ K} \tag{2}$$

T is a critical parameter that determines the capability of detection and affects the magnitude of S/N. T is the thermal temperature term in the Stefan-Boltzmann expression for radiant emittance as will be described later.

The background temperature T_B, as viewed by the phase center of the feed and by the extension of the G_{max} axis, is a thermodynamic temperature which changes from instant to instant as the collecting aperture articulates over any arbitrary scanning pattern of the surface. T_B defines the instantaneous thermodynamic background temperature upon which the emitting object is superposed at any instant of time.

Consider an arbitrary scanning pattern for the collecting aperture where the measured values of T_B are assigned a grid pattern with corresponding values of scan position by G_{max}. What is thus formed is a matrix showing the temperature variations of T_B, with respect to the position of G_{max}, as its extension intersects the surface. This matrix is of critical importance in the determination of clutter power magnitudes. From the matrix, a hyperplane function is computed from which the estimated instantaneous values of the background temperature variations and the standard error of estimate (SEE) are computed.

The mean temperature of the hyperplane, at the corresponding coordinates of the emitting object, provides an estimate of T_B. The SEE provides an estimate of the clutter power magnitude with which T is competing. The SEE also furnishes information as to the magnitude of the clutter power that enters the sidelobes.

A detailed investigation of T_B variations, in the immediate vicinity of the emitting object, provides a local estimate of the clutter power magnitude. For example, a least squares fit to a sample matrix comprised of all the values for T_B in the immediate vicinity of the emitting object will yield a local SEE that will serve as an estimate for the local clutter magnitude.

These matrix operations are trivial mathematical manipulations yet they furnish precise estimates for the signal and clutter terms needed to compute S/N.

The background temperature T_B, against which the emitting object is always viewed, is of extraordinary importance and is worthy of further comment. From Fig. 1, the geometrical path that engages the emissive contributors to T_B include: the downwelling path, the surface material, and the upwelling path. All contributions are directed to the phase center of the collecting aperture.

The angle of incidence Θ_i also affects T_B. Variations in Θ_i change the lengths of the downwelling and the upwelling paths through the atmosphere and affect the apparent area of the emitting object.

The radiant emittances of certain surface materials are polarization selective. The horizontal and vertical components of the polarization vector change with respect to Θ_i.

The expression for T_B shows the separate contributions from each of the segments within the propagation path it traverses. T_B illustrates explicitly the exact transfer of thermodynamic temperature from all the media it engages (including the Cosmic Background) and refers all contributions to the phase center of the feed. The phase center, therefore, views the emitting object against a composite temperature background in which all of the emissive contributors along the path are viewed as one temperature. The emission from, and the variabilty of, the atmospheric loss constituents appear in T_B.

As the G_{max} axis is repositioned, even by very small increments, the emissive contributors to T_B along the geometrical path may be expected under certain circumstances, to exhibit dramatic temperature changes. Large temperature changes occur when the geometrical path viewed by G_{max} intercepts abrupt changes in land features or land-water and ice-water boundaries.

T_B is always to be regarded as an estimator because most, if not all, of its terms possess statistical properties.

Ultimately, we must deal with the clutter power that arrives at the output terminals of the feed because it influences the value of N, in S/N. Clutter power arrives through G_{max} as statistical variations in the amplitude of T_B. Also, the sidelobes, whose central gain axes intercept the atmosphere and the Earth, contribute clutter power in summation with the clutter power arriving through G_{max}.

Clutter power is generated by the radiant emittances from thermal discontinuities on the surface, especially while the collecting aperture is articulating. The magnitude and the character of the clutter are relegated to an analysis of the primitive outputs of the receiver. Typically, the clutter power exceeds the RMS noise level of the receiver.

THE POWER TRANSFER EXPRESSIONS

The geometry and the criteria that affect the transfer of power from the emitting object to the collecting aperture, in orbit, are illustrated in Fig. 1 and have been discussed in the foregoing material.

What we choose to deal with in this section is the development of the mathematical expressions that show the manner in which the signal power that is radiated from the emitting object is combined with the noise and clutter elements to form the signal-to-noise ratio as referenced to the terminals of the feed aperture.

The signal-to-noise ratio, with the predetection bandwidth as a supporting parameter, contains all the information that is needed by and is available to the user...the probability of detection, the kind of information that is available about the emitting object, the information channel capacity, and its measurement precision.

In the development of the mathematical processes that finally determine the S/N, it is necessary to be consistent and unambiguous in the determination of what is signal power and what is noise power. Mostly it will be obvious but occasionally clarifications are required.

The radiant emittance W_{obj} of the emitting object is the signal power that is transferred over slant range R_S and distributed over a solid angle of 4π steradians where the signal power finally arrives as a microwave wavefront at the collecting aperture A_C.

The collecting aperture intercepts the signal power that is available in the power density W_C of the wavefront and transfers it to the phase center of the feed and its output terminals. Upon arrival at the feed terminals, the signal power P_S is combined with the noise power P_N in a ratio where P_S/P_N is defined as S/N, where N consists of both clutter power and receiver noise power components.

The S/N is formed at the feed terminals with the consideration that the signal power has suffered all of the propagation losses in the transit of R_S and, further, that it has been affected by the inefficiencies in the collecting aperture. Receiver noise contributions that affect the S/N are referred forward to the feed terminals with the underlying assumption that the receiver, operating as an amplifying device, is perfect.

The radiant emittance of the emitting object, Fig. 1, is given by

$$W'_{obj} = \varepsilon\sigma T^4, \text{ W/m}^2 \tag{3}$$

where

ε = is the emissivity of the surface material, dimensionless

σ = 5.67032E-08 $\text{W/m}^2\ \text{K}^4$, the Stefan-Boltzmann Constant

$T = \left|T_{obj} - T_B\right|$, K, from (2)

The emitting object radiates graybody energy through the normal of its disk figure.

T is expressed as an absolute value because under certain circumstances T_{obj} may be greater or less than T_B.

Because the diameter of the disk ℓ is $<< R_S$, the angle subtended by ℓ , as viewed by the phase center of the collecting aperture, is very small and is reckoned in microradians. For this reason, the area of the emitting object A_{obj} operates as a point source.

The power radiated through the normal vector of the emitting object (i.e., $\Theta_i = 0$) is given by

$$W_{obj} = \varepsilon \sigma T^4 A_{obj}, \text{ watts} \tag{4}$$

From Lambert's Cosine Law, the power radiated from the emitting object at Θ_i is

$$W_\Theta = W_{obj} \cos \Theta_i, \text{ watts} \tag{5}$$

Recasting the terms of A_{obj} to express its diameter rather than its area

$$A_{obj} = \frac{\pi \ell^2}{4}; \text{ m}^2 \tag{6}$$

Substituting the terms of (5) and (6) in (4) and recasting

$$W_{obj} = \frac{\varepsilon \cos \Theta_i \, \sigma \, T^4 \, \pi \ell^2}{4}, \text{ watts} \tag{7}$$

The power density in the wavefront W_C that arrives at the collecting aperture after transiting R_S, and after being redistributed over 4π steradians, is expressed by

$$W_C = W_{obj}\left(\frac{1}{4\pi\ R_S^2}\right),\ W/m^2 \qquad (8)$$

The signal power P_S arrives at the terminals of the feed after having been intercepted by the collecting aperture A_C and after having suffered the collecting aperture inefficiency. The power density in the wavefront is also diminished by atmospheric attenuation in the upwelling path L_{au} during its transit of R_S.

η is defined as the solid angle main beam efficiency of the collecting aperture and the feed structure and it mainly represents the fraction of the signal power that arrives within the first nulls of the directional diagram. η importantly influences the magnitude of G_{max} and also the level of the clutter power that enters the sidelobes.

Frequently, the term "antenna efficiency," as it is expressed as an operator to modify the size of the collecting area in radar and communications antennas, is confused with η.

Introducing A_C and η in (8)

$$P_S = W_C\,(A_C\,\eta),\ \text{watts} \tag{9}$$

P_S is redefined as S, the signal power, in the expression S/N.

Expanding the terms of (9)

$$P_S = W_{obj}\left(\frac{1}{4\,\pi R_S^2}\right)(A_C\,\eta)\left(\frac{1}{L_{au}}\right),\ \text{watts} \tag{10}$$

$$= \frac{\pi\sigma\varepsilon\ \cos\Theta_i T^4 \ell^2\ (A_C\,\eta)}{4(4\,\pi R_S^2)L_{au}} \tag{10a}$$

$$= \frac{\sigma\varepsilon\ \cos\Theta_i T^4 \ell^2\ (A_C\eta)}{16\ R_S^2\ L_{au}} \tag{10b}$$

Equation (10) expresses the power transferred from A_{obj} at temperature T over slant range R_S which is intercepted by A_C at G_{max}. The power is expressed as P_S and is referred to as the signal power from the emitting object as referenced to the terminals of the feed.

The noise power P_N that competes with the signal power P_S at the terminals of the feed aperture is composed of two noise components:

(1) Clutter radiances that enter the directional diagram of the antenna through the principal lobe and the sidelobes. Clutter noise originates as statistical variations in T_B, noting

that the statistical noise components in T_B include the radiant emittances from clutter originating on the surface and from atmospheric constituents in both the downwelling and the upwelling paths.

Stochastically, and by rigor, the total clutter radiances are expressed as the standard error of estimate SEE of the hyperplane formed by variations in T_B in the immediate vicinity of the emitting object.

In the mathematical development given here, T_B is expressed in kelvins, and for consistency, so is the clutter T_{clut}.

(2) Receiver noise that is generated by receiver amplifiers or by receiver components. Receiver noise is referred to the terminals of the feed.

The total noise power originating from clutter and from receiver noise are combined as P_N by an orthogonal average in (1).

The S/N is expressed by P_S/P_N and is formed by combining (10) and (1)

$$S/N = \frac{W_{obj} \; (A_C \; \eta)}{(4 \; \pi R_S^2) \; L_{au} \; k \; T'B} \text{, dimensionless} \tag{11}$$

where k T´B is the total noise power originating from clutter and receiver noise. B is defined as the predetection bandwidth of the receiver, in Hertz.

Rewriting (11) and collecting terms

$$S/N = \frac{\pi \sigma \varepsilon \cos \Theta_i T^4 \ell^2 (A_C \eta)}{4(4 \pi R_S^2) L_{au} k T' B} \tag{11a}$$

$$= \frac{\sigma \varepsilon \cos \Theta_i T^4 \ell^2 (A_C \eta)}{16 k R_S^2 T' B L_{au}} \tag{11b}$$

by combining constants

$$= \frac{2.57 \times 10^{14} \varepsilon \cos \Theta_i T^4 \ell^2 (A_C \eta)}{R_S^2 T' B L_{au}} \tag{11c}$$

S/N is the parameter that controls the probability of detection of the emitting object; further, it specifies the quality and accuracy to which the intrinsic properties of the emitting object can be measured.

A range of detection statistics are keyed to S/N as a parameter. The statistics are different for articulating systems than for point and acquire systems. For example, in an articulating system, as G_{max} encounters an emitting object on the clutter hyperplane, the following questions arise:

What is the probability of detecting a noise signal in noise (clutter and receiver noise) where the noise signal is produced by an emitting object of a specified area and temperature during articulation?

What are the false alarm criteria that affect the detection? What S/N ratio is required for a specified false alarm rate with probability of detection as a parameter?

Detection systems, in the microwave region, typically design for a 15-dB S/N, or greater, where high probabilities of detection and precise measurements of the detected body are required.

Equation (11) can be recast in various ways to determine other parameters...given a specified S/N. The diameter of the emitting object ℓ, or the required area of the collecting aperture A_C, can be deduced if sufficient information is available, or can be inferred, from the remaining terms in (11). Recasting (11) for A_C

$$(A_C\ \eta) = \frac{R_S^2\ T'B\ L_{au}\ (S/N)}{2.57 \times 10^{14}\ \varepsilon\ \cos\ \Theta_i T^4 \ell^2}\ ,\ m^2 \tag{11d}$$

or for the diameter of the emitting object ℓ

$$\ell^2 = \frac{R_S^2\ T'B\ L_{au}(S/N)}{2.57 \times 10^{14}\ \varepsilon\ \cos\ \Theta_i T^4\ (A_C\ \eta)}\ ,\ m^2 \tag{11e}$$

THE DETECTION SYSTEM OPERATING WAVELENGTH

Ultimately, we must deal with the practicalities of retrieving the signal power that arrives in the wavefront which is incident on the collecting aperture. The signal power retrieval must be accomplished with high efficiency, otherwise, the S/N will be degraded.

The signal power retrieval efficiency of the collecting aperture is different from η, the solid angle main beam efficiency, as shown in (11). η expresses the fraction of the power that is intercepted between the first nulls of the principal lobe of the directional diagram over the total solid angle of 4π steradians.

The signal power retrieval efficiency factor is patently an undefined quantity. It increases asymptotically as a function of the number of wavelengths that are distributed across the diameter of the collecting aperture. Mainly, the signal power retrieval efficiency factor is influenced by the illumination taper that is projected on the surface (edge) of the collecting aperture by the feed pattern. Both the signal power retrieval efficiency factor and η operate in consonance, with the same sign of the slopes, and their magnitudes are importantly keyed to the number of wavelengths that occur across the diameter of the collecting aperture.

In the discussion that follows, a prime focus antenna configuration is assumed with a paraboloidal figure and with a circular aperture.

As the operating wavelength is decreased and as the number of wavelengths increase across the diameter of the paraboloid, the aperture illumination factor decreases the intensity of the wavefront at the edges of the collecting aperture. Simultaneously, the power retrieval efficiency factor and η increase asymptotically.

As the number of wavelengths across the diameter approach approximately 100, the edge illumination intensity decreases and slowly approaches -30 to -40 dB with respect to the central illumination of the collecting aperture. At the same time η approaches 1. If the number of wavelengths are further increased, there is little change in either the edge illumination or in η.

As the illumination taper concentrates more and more of the received energy within the central area of the collecting aperture, less and less energy is distributed into the sidelobes and the clutter components are also reduced.

What is suggested by the foregoing discussion is that when the wavelength distribution across the collecting aperture approaches approximately 100, there is little improvement in either the collecting efficiency of the aperture or in η if the number of wavelenghts is further increased. From this, an optimum operating wavelength, λ_{opt} is suggested by

$$A_C = \frac{\pi D_C^2}{4}$$

where DC is the diameter of the circular figure of the paraboloid in meters,

$$\lambda_{opt} \approx \frac{D_C}{100} \approx \left(\frac{4\ A_C}{\pi\ 10^4}\right)^{1/2}, \text{ m} \tag{12}$$

Expression (12) expresses the relationship that as A_C increases λ_{opt} also increases.

If the operating wavelength λ_o of the collecting aperture is further decreased to produce a larger and larger number of wavelengths across the diameter, beyond the 100-wavelength criterion, other factors of a system and instrument related character operate to decrease the S/N. For example, L_{au} may increase because of atmospheric attenuation and the dissipative losses in the receiving system may increase because of shorter wavelength operation.

The optimum wavelength criterion is intended to maximize the S/N for detection purposes.

Where the choice of the operating wavelength is influenced by the desire to receive the emission from a particular skin depth in the surface material...then the optimum wavelength criterion has no relevance. Similarly, when multiple wavelength operation is desired, for any reason, then the optimum wavelength criterion has no relevance.

THE RANGE OF THE NOISE VARIABLES

The range of the noise variables as identified in (11a), is discussed as they apply to observations of the emitting object from Earth orbit or from aircraft.

Any application of (11) should ensure that the observed object appears as a point source in the sense that the angle subtended by the object, from the phase center of the feed, should be very small and preferably dimensioned in microradians or smaller angular units.

Expression (1) identifies the noise terms with which the signal power must compete, that is, the clutter power that enters the directional diagram and also the intrinsic RMS noise level of the receiver. As has been mentioned previously, the receiver noise is typically lower than the clutter and in an orthogonal average the clutter component of the noise will dominate the value of T.

The solid angle beam efficiency factor η importantly influences the magnitude of the clutter that enters the sidelobes.

The standard error of estimate SEE of the T_B hyperplane, in the vicinity of the emitting object, determines the magnitude of the clutter emanating within the central response of the directional diagram of the collecting aperture. In practice, the sidelobe clutter and the clutter from the T_B hyperplane are not separately identifiable and are therefore manipulated as a composite temperature.

Because the receiver noise is expressed as a temperature in widespread practice, we choose to be consistent and express the clutter magnitude also as a temperature. Expression (1) summarizes the manner in which the total clutter and receiver noise are combined as P_N.

Operating experience with orbiting antenna systems, in the microwave region, has shown clutter temperatures, as referenced to the terminals of the feed aperture, to range from approximately 0.5 to 7 K. The solid angle beam efficiencies of the collecting apertures for these systems have slightly exceeded 0.9. The clutter magnitudes are influenced by operation over a range of sea surface roughness conditions when the sea areas are known to be significantly remote from land. Observations over land and ice have included areas that are known to contain an abundance of land-water or land-ice boundaries.

The clutter temperatures are deduced from the SEE of the T_B hyperplane as given by a sampling matrix which was prepared by randomly sampling the entire areal extent of the image.

AN APPLIED EXAMPLE

In the system planning stages for passive observations from earth orbit, we must first deal with the user requirements as they relate to the class of objects to be detected and measured. The user is obliged to define and provide the expected physical and thermal characteristics of the objects he proposes to observe.

Primary among the chara....istics needed by the system designer are the areal extent(s) of the object(s) and the range(s) of their temperature differences T with respect to the background temperature T_B. From these data and from the earth-orbit geometry, the passive system designer can size the requirements for the antenna system and for the receiver.

We proceed with the example by selecting a worst case object to detect and measure among the objects supplied by the user.

Given a specification to detect a circular object with a 2-kilometer diameter and with a minimum temperature difference with respect to its background T_B of 2 K, we proceed to determine the size of the collecting aperture that is required.

From (11d), which is a recasting and simplification of (11), the required area for the collecting aperture is computed. Expression (11d) also contains terms that must be satisfied in addition to those given by the user. The terms that relate to the orbit-to-surface geometry are satisfied along with some estimates of the clutter magnitudes which are derived from previous experience.

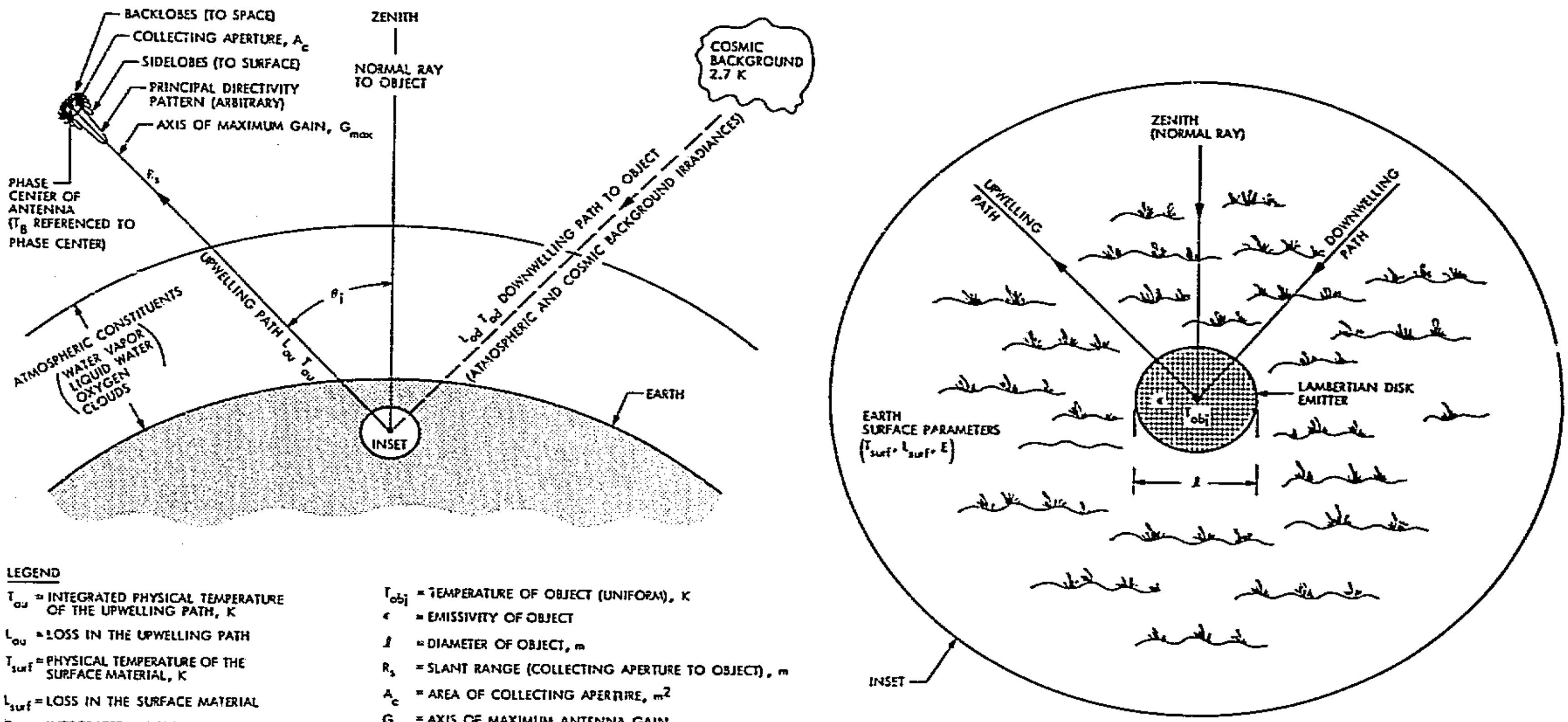
The detection and measurement are presumed to be executed with an articulating collecting aperture.

The following data, entered into (11d) to solve for A_C, yield a value of $0.33\ m^2$ for A_C (the model is referenced to Fig. 1):

o	Altitude of the collecting aperture	708 km
o	Slant range R_S to the emitting object	1000 km
o	Incidence angle Θ_i	48 deg
o	Required S/N	10 dB
o	Diameter of the emitting object ℓ	2000 m

o	Difference temperature of the emitting object T with respect to the background temperature T_B	2 K
o	Emissivity of the emitting object ε	0.98
o	Predetection bandwidth of the receiver B	100 MHz
o	Orthogonal average of receiver and clutter noise T'	3 K
o	Clear weather attenuation in the upwelling path L_{au}	1.35 dB (1.07)
o	Solid angle main beam efficiency factor η for the antenna	0.90

From the rationale given for (12), the optimum wavelength λ_{opt} (6.5 mm) is adopted for the operating wavelength λ_o.



LEGEND

T_{ou} = INTEGRATED PHYSICAL TEMPERATURE OF THE UPWELLING PATH, K

L_{ou} = LOSS IN THE UPWELLING PATH

T_{surf} = PHYSICAL TEMPERATURE OF THE SURFACE MATERIAL, K

L_{surf} = LOSS IN THE SURFACE MATERIAL

T_{od} = INTEGRATED PHYSICAL TEMPERATURE OF THE DOWNWELLING PATH, K

L_{od} = LOSS DOWNWELLING PATH, K

T_B = THERMODYNAMIC TEMPERATURE OF THE BACKGROUND, K

T_{obj} = TEMPERATURE OF OBJECT (UNIFORM), K

ϵ = EMISSIVITY OF OBJECT

ℓ = DIAMETER OF OBJECT, m

R_s = SLANT RANGE (COLLECTING APERTURE TO OBJECT), m

A_c = AREA OF COLLECTING APERTURE, m^2

G_{max} = AXIS OF MAXIMUM ANTENNA GAIN

θ_i = INCIDENCE ANGLE, deg

$$T_B = \underbrace{\frac{T_{cosmic}}{L_{od}\,L_{surf}\,L_{ou}}}_{\text{[COSMIC]}} + \underbrace{\frac{T_{od}\,(L_{od}-1)}{L_{od}\,L_{surf}\,L_{ou}}}_{\text{[DOWNWELLING]}} + \underbrace{\frac{T_{surf}\,(L_{surf}-1)}{L_{surf}\,L_{ou}}}_{\text{[SURFACE]}} + \underbrace{\frac{T_{ou}\,(L_{ou}-1)}{L_{ou}}}_{\text{[UPWELLING]}}, \text{ K}$$

WHERE: E = EMISSIVITY

$$L_{surf} = \frac{1}{1-E}$$

SUBSCRIPTED L SYMBOLS ARE DISSIPATIVE LOSSES EXPRESSED AS A NUMBER > 1.

Fig. 1. Power transfer expressions (detection of emissive objects)

$$(S/N) = \frac{\pi \sigma \epsilon \cos \theta_i T^4 \ell^2 (A_c \eta)}{4\left(4\pi R_S^2\right) L_{au} k T' B}, \quad \text{DIMENSIONLESS} \qquad (11a)$$

$$(S/N) = \frac{2.57 \times 10^{14} \epsilon \cos \theta_i T^4 \ell^2 (A_c \eta)}{R_S^2 T' B L_{au}}$$

WHERE

σ	=	5.67032E+08	STEFAN-BOLTZMANN CONSTANT.
ϵ	=	EMISSIVITY OF EMITTING OBJECT (NORMAL INCIDENCE).	
θ_i	=	ANGLE OF INCIDENCE, DEG.	
T	=	DIFFERENCE TEMPERATURE: EMITTING OBJECT TEMPERATURE MINUS THE BACKGROUND TEMPERATURE $\lvert T_{obj} - T_B \rvert$, K	
ℓ	=	DIAMETER OF EMITTING OBJECT, m	
A_c	=	AREA OF COLLECTING APERTURE, m^2	
η	=	SOLID ANGLE MAIN BEAM EFFICIENCY.	
R_S	=	SLANT RANGE, m	
L_{au}	=	ATMOSPHERIC ATTENUATION, A NUMBER > 1.0.	
k	=	1.380662E-23	BOLTZMANN CONSTANT.
T'	=	CLUTTER PLUS RECEIVER NOISE, ORTHOGONAL AVERAGE, K	
B	=	PREDETECTION BANDWIDTH, HERTZ	

Fig. 2. Power transfer equations (surface to orbit)