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SOME QUANTITATIVE ASPECTS OF VERIFICATION

by

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by G.R.Lindsey

In past decades most of the problems which have impeded the negotiation of arms control agreements and the arrangements for verification of the agreements have been of a political nature, and many of these have been eased by recent developments in international relations. But some of the problems are technical. These include the limitations of the capabilities of the sensors used to obtain the information needed for verification. Another group of important technical problems are of a more analytic and mathematical nature, and are concerned with the relationship between the scale and conduct of the verification activities and the effectiveness and confidence with which they will be able to confirm compliance or to discover violations of the agreement.

Nuclear physics, chemistry, and biology have obvious parts to play in both the problems and the solution of the needs of verification for various arms control agreements. The following discussion will identify some of the quantitative aspects of the verification of arms control agreements, and suggest opportunities for mathematics and statistics to make contributions.

DEFINITIONS OF WEAPONS OR ACTIVITIES TO BE SUBJECT TO LIMITATION

One problem, with many ramifications, is that of defining the weapons to be prohibited or limited. This can be done by identifying existing systems by name, or by words describing the role of the weapon, but in many cases there is such a variety of weapons of the relevant general category that only a particular subset is chosen for control. And, if the agreement is to last for more than a few years, modernization will introduce new weapons and changes to existing weapons, for which the agreed definition may now be ambiguous or even inappropriate.

As an alternative to the individual identification of weapons to be prohibited, it may be possible to agree on certain quantitative performance characteristics, and set limits to these, either for individual weapons or for the total force.

An example is the provision to control modernization of ICBMs. START defined a new type of ICBM to be one differing from the existing inventory in the type of propellant, number of stages, length, largest diameter, launch weight, or throw-weight, and specified the percentage changes that could qualify a missile as "a new type".

SALT I, SALT II, and START took successive steps towards the definition of a "heavy ICBM", established in 1991 at a launch weight over 196,000 kg or a throw-weight over 4,350 kg, and START set a limit of 3600 tons to the aggregate throw-weight of all deployed ICBMs and SLBMs.

The Threshold Test Ban Treaty set the maximum permissible yield of an underground nuclear test at 150 kilotons.

CFE defines its treaty-limited items with descriptive words, supplemented by a few stipulations on weapon calibre and total vehicle weight.

The ABM Treaty has encountered severe problems over definitions which probably seemed quite adequate in 1972. Modernization and replacement of permitted ABM systems or their components was allowed, but the parties undertook not to develop, test, or deploy ABM systems or components which were sea-based, air-based, space-based, or mobile land-based. The Treaty also forbids the development and testing "in an ABM mode" of systems not originally designed for ABM application.

In the twenty years since the signing of the Treaty, intensive research and development programs have revealed possible ABM applications of other physical principles not contemplated in 1972, of sensors and weapons based in space, and of the extension of systems originally designed for defence against aircraft (which is permitted) to be given an ABM capability. Questions of interpretation have arisen as to the definition of a component, and of "testing in an ABM mode"[1]. And the growing concern over the need to provide defence against short-range tactical (as opposed to long-range strategic) ballistic missiles has made the ambiguities of the ABM Treaty all the more unsatisfactory.

What seems to be needed is the use of provisions established in the ABM Treaty to open discussions to clarify the definitions and fix unambiguous and verifiable limits to what will be allowed in testing as well as deployment, including the placing of sensors in space as well as on the ground, and allowing for rapid progress in provision of defence against tactical ballistic missiles.

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[1] One suggestion called the "Foster Box" sets a limit to the altitude of the interception and the speed of the target for a test. The figures of 70 km altitude and 3 km/sec speed have been used to illustrate boundaries inside of which a test would not be considered to be useful for defence against strategic ballistic missiles. See "Rationalized Speed and Altitude Thresholds for ABM Testing", by Herbert Lin, *Science & Global Security*, 2, 1, 1990, pp.87-101.

THE MECHANICS OF VERIFICATION

A number of very different types of verification operations are in use or under consideration today[2]. They include surveillance over large areas by sensors carried in satellites, aircraft, or ships, or based on or under the ground, and able to detect objects or receive signals at long ranges; on-site inspections of brief duration which may occur at short notice; and continuous portal perimeter monitoring at exits from manufacturing facilities or military bases. The objects of verification are treaty-limited equipment of various kinds, or controlled materials, but the monitoring includes observation of testing of both experimental and operational systems, as well as the deployment of weapons.

Detection of underground nuclear explosions is carried out with seismic instruments in widely dispersed fixed sites. Large-yield nuclear explosions can be detected with high probability, while the problems of discriminating low-yield explosions from naturally occurring subterranean earth shocks, based on the readings of instruments located far from the site of the explosion, lie in the fields of geology, physics, and statistics[3]. Accurate estimation of the yield requires emplacement of sensors underground and close to the site of the explosion, with the cooperation of the testing authorities.

Above-ground nuclear explosions can be detected and located by sensors in a constellation of high-altitude satellites, providing complete global coverage. Radio-frequency receivers in the same orbits are able to record signals from communications transmitters and radars.

More can be learned from the observation of missile test flights than by close-range examination of the outside of the missiles themselves, especially if it is possible to track the flight on radar, observe the trajectories of multiple reentry vehicles, and collect telemetry signals transmitted for analysis by the testing organization.

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[2] See, for example, *Verification Report 1991: Yearbook on arms control and environmental agreements*, (ed.) J.B.Poole, VERTIC, London, 1991. Also "Verifying the INF Treaty and START", by Owen Greene & Patricia Lewis. Chapter 5 in *A Handbook of Verification Procedures*, (ed.) Frank Barnaby, Macmillan, London, 1990., pp.235-263.

[3] See, for example, "Verification of a Comprehensive Test Ban", by Roger Clark & John Baruch. Chapter 3 in A Handbook of Verification Procedures. *op. cit.*, pp.37-178.

Detection and identification of objects such as missile silos, warships, and large aircraft on their bases can be accomplished from surveillance satellites in low earth orbit[4]. But celestial mechanics demands that such satellites pass quickly over the area of interest, and cannot repeat their visit until many hours have elapsed. To obtain the resolution with electro-optical sensors adequate for identification of objects such as tanks or mobile missiles, it is necessary to concentrate the imagery into a comparatively narrow field of view. A single satellite can do no more than sample narrow paths (swaths) across the area of interest, and this at comparatively long time intervals. Moreover, optical sensors will be unable to see targets through cloud cover, and many require daylight.

We are faced with problems of estimating the magnitude of a total deployment never wholly visible, using small samples obtained at intermittent occasions.

The path of a satellite orbit can only be altered by expenditure of some of a very limited quantity of manoeuvring fuel, and the main ability to control surveillance coverage will be by adjusting the angles and widths of the swaths beneath the satellite track observed by the sensors.

Aircraft can operate sensors much closer to the ground than can space vehicles, and can control their flight path to spend more time in areas of interest. But, unlike satellites, their use for verification depends on the permission and cooperation of the inspected party, and is likely to involve limitations to the types of sensors carried, the flight paths, altitudes, and times of overflight[5].

Analysis of the records obtained from both spaceborne and airborne sensors will benefit from many aspects of signal processing, image enhancement, and data fusion.

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[4] See. for example, "The Use of Satellites for Verification", by Caesar Voute. Chapter 2 in A Handbook of Verification Procedures, *op. cit.*, pp.7-36.

[5] See for example *Verification Technologies: Cooperative Aerial Surveillance in International Agreements*, US Office of Technology Assessment, Washington, 1991.

THE STRATEGY OF VERIFICATION

Arms control can only be negotiated, agreed, and implemented with a certain degree of cooperation from all the parties concerned (although it may be a unilateral type enforced by powerful parties in the wake of a military victory[6]). Some degree of verification can be carried out without cooperation, relying on "national technical means"[7], but the most effective verification will require a certain amount of intrusiveness, which the inspected party may accept in a cooperative manner or may resent and impede.

Verification, like the procedures for auditing of the accounts of a reputable commercial organization, should be designed for the possibility that there may be erroneous accounting, deception, or concealment of information, and that these should not escape discovery.

Presumably, if there has been compliance, the verifying party wishes to confirm that this is the case, a conclusion welcomed by both parties. But if there has been a violation, the verifier wishes to detect it, an outcome unwanted by the violating party. However, if his means of collecting evidence are imperfect, the verifier faces the possibility of two types of error. One is to fail to detect a violation when one has occurred, the other is to conclude that there has been a violation when the inspected party is actually complying. Both of these last two outcomes are damaging to the interests of the inspecting party. In the first case he may find himself at an unexpected disadvantage in a military confrontation, while if he issues a false alarm, relations will be impaired and he will be subject to embarrassment. The inspected party will gain by a failure to detect an actual violation, but it is not obvious whether an unjustified accusation would be to his advantage or disadvantage.

This is a situation well suited for analysis by the theory of games, decision theory, and statistical inference. We are dealing with non-zero sum games with imperfect information. Non-zero sum implies that while the interests of the participants are opposed in some respects, there are also situations in which both may gain or lose together, which is very much the case with arms control.

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[6] The best example of this is the imposition by the United Nations Special Commission on Iraq (UNSCOM) of inspections of weapon sites and research facilities, following the Gulf War.

[7] Several treaties contain undertakings not to interfere with NTM.

The theory of games has been applied to a number of problems of arms control and verification by mathematicians such as Professor Avenhaus. Insights are obtained into optimum strategies for both inspectors and inspectees. Examples include best allocation of search effort, best scheduling of on-site inspections, procedures for auditing inventories of fissile materials, estimating the effect of combining imperfect procedures of detection, and the relationship between the costs (or penalties) for various outcomes and the resulting behaviour[8].

The information available to the inspecting party may be imperfect due to efforts on the part of the inspected party to camouflage or conceal objects, or use otherwise deceptive measures, or may originate from the inability of sensors to detect objects or of interpreters to identify them correctly. However, the greatest problem for verification is the inability to obtain high-resolution imagery over the entire area in which treaty-limited equipment may be deployed, or to inspect all of the relevant sites, within a brief interval of time. This limitation forces the verifiers to estimate the total population from information obtained based on comparatively small samples, using the methods of statistical sampling theory. However, the methods developed for quality control do not take into account the possiblity that the objects under observation may act in a manner intended to interfere with the process.

STATISTICAL SAMPLING

If the number of surveillance satellites and the width of the swaths which they could sweep with 100% assurance of detecting a particular type of weapon were great enough to provide complete cover of a specified area in a short time, say one week, then it would be possible to verify the number of weapons deployed in the area, if we assume that no significant change could be made in a time interval as short as one week.

In the cases of ICBM silos, airfields, and other large fixed easily recognized objects, it has been possible to provide nearly complete cover, accumulated over a period much longer than a

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[8] "Implementation of Verification Methods", by Patricia M Lewis. Chapter 9 in *Verification of Conventional Arms Control in Europe: Technological Constraints and Opportunities*, (eds.) Richard Kokoski & Sergey Koulik. SIPRI Westview Boulder 1990. pp.17-55. Also *New Research in Arms Control Verification using Decision Theory: Site Selection for On-Site Inspection under CFE I and Interaction Among Verification Methodologies* External Affairs & International Trade Canada, Ottawa, 1991.

week,. but short in comparison to the time needed to construct such a facility.

However, for most other weapons which might become the objects of arms control, such favourable circumstances do not apply. High resolution imagery is required to detect and identify the objects of interest, and the probability of detection will be less than 100%, even when the object is in the geometrical field of view of the sensor. High resolution implies a narrow swath swept by the sensor, a limited area covered in a day, and therefore many days to cover all of the area of interest. Most of the wanted targets are mobile, so that over a period of many days the geographical deployment can be drastically altered. The best that the verifier can collect is a series of "snapshots" of small samples of the area. From this limited evidence it will be necessary to estimate the true situation, and infer whether the inspected party is complying with the agreement.

For most other means of verification an analogous situation applies[9]. In connection with the CFE agreement, aerial inspections and on-site inspections are being planned on a scale to allow 10% to 15% of the sites to be inspected in a period of one year. The small percentage makes estimation by sampling imprecise, and the time scale of a year allows for considerable changes to occur, the most dangerous being a substantial "breakout" of rearmament and buildup.

A special case of statistical sampling is presented for verification of a total ban of a particular weapon[10]. Here the discovery of a single prohibited item represents a clear violation. A series of samples, each producing no detection, builds up increasing confidence that no weapons are present anywhere, but cannot make this conclusion a certainty.

When a specified number of weapons is permitted, mobility adds greatly to the difficulty of verification. It prevents a steady accumulation of knowledge as to how many items are in

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[9] "Verifying NATO-Warsaw Pact Force Reductions and Stabilising Measures", by Jonathan Dean. Chapter 7 in A Handbook of Verification Procedures. *op. cit.* pp.310-346.

[10] After much negotiation over the numbers of intermediate-range nuclear weapons that would be permitted, the INF Treaty adopted the "zero option", for a total ban. These weapons were mobile, and verification by satellite surveillance, without on-site inspection, would have been inaccurate. But with a total ban and intrusive OSIs at both weapon sites and production facilities, there is great confidence in the verification provisions.

known locations[11]. It makes it easier for the inspected party to remove or hide weapons to escape detection[12], and to build up and store a hidden inventory which could be deployed quickly.

In addition to being able to arrive at an estimate of the total number of controlled weapons deployed, verification also needs to be able to detect a significant increase (commonly labelled as a "breakout"), within a reasonably short time of its occurrence.

The effort allowed for aerial or on-site inspection can be concentrated geographically by a reduction in the area or number of declared sites on which limited weapons will be permitted[13]. This implies that discovery of a single weapon outside of the agreed territory would constitute a violation, so that reduced coverage of the forbidden area or sites would probably be sufficient to deter illegal deployment. Geographical concentration of the deployed weapons would be of limited assistance to satellite surveillance, since it is not feasible to make frequent adjustments to the trajectory[14].

To illustrate the problems of statistical sampling, some specific examples are presented in the following Annex.

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[11] If a small number of weapons were permitted, nearly simultaneous detection of a greater number would signal a violation. But if the weapons could change their locations during the period during which the detections were made, it would not be known how many weapons had been detected more than once.

[12] Some mobile weapons such as tanks routinely carry camouflage netting to make them less visible when they park.

[13] START requires road-mobile ICBM launchers to be based in restricted areas occupying no more than 5km^2, enclosed by a deployment area no larger than 125,000 km^2. No more than ten launchers can be in any one restricted area.

[14] Some modifications to the coverage may be possible by redirecting the offset angle of the swath being surveyed.

ANNEX

SATELLITE SURVEILLANCE OF MOBILE WEAPONS

To illustrate some of the points described above, consider the example of an arms control agreement limiting the number of a particular type of mobile weapon to N_0 = 200, with their deployment to be confined to a large area A located at latitudes in the neighbourhood of 50° North.

Suppose that verification is to be carried out by one photoreconnaissance satellite orbiting with a period of 90 minutes and with an inclination of considerably more than 50°, and able to detect the missiles located within a swath 75 km wide beneath the path of the satellite when they are illuminated by daylight and not obscured by cloud cover.

The satellite will cross the 50°N parallel of latitude travelling from south to north at intervals of 90 minutes, during which the rotation of the earth will move area A eastward by 1600 km. In twenty-four hours the earth in the vicinity of latitude 50°N will be "sampled" by the surveillance swath with a density of about 75/1600, or 4.7%[15]. There will be an equal number of crossings in a southbound direction, but since only about half of all the crossings will be in daylight, we can relate the opportunities for detection to the number of northbound crossings[16]. A factor needs to be applied to allow for cloud cover, so that the "sampling density" for detections will often be well below 5%. On the average a location in area A will be overflown by a surveillance swath in daylight at intervals of about 21 days, some of which will be in poor visibility. Any particular weapon may be detected about once a month.

To demonstrate the principles of estimation by statistical sampling, suppose that the satellite operates for m=100 days with perfect visibility, and obtains a sampling density for detection of S=5%. If the number of weapons deployed were exactly N=200, distributed randomly throughout area A, the number detected each day might be 8, 9, 10, 11, or 12, with fewer or more than this on some occasions, and with the mean value close to SN = (5% of 200) = 10. The verifying party would add up the number of detections

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[15] The sampling density will be increased by a factor depending on the inclination of the orbit and the latitude, which becomes important at latitudes approaching the inclination angle.

[16] A factor can be applied to allow for the hours of daylight (or the hours during which the sun is above some specified elevation angle) at different latitudes at different times of the year, but, averaged over one year, half of the crossings will occur with the sun above the local horizon.

made during the 100 days, divide by 100, and obtain the measured mean number $\langle N \rangle$ for one day's observation. The estimate N_E of the total number of missiles deployed in A would be

$$N_E = \langle N \rangle / S = 20 \langle N \rangle.$$

If $\langle N \rangle$ has been based on m=100 days of observations, statistical theory predicts that the estimated N_E will have a standard deviation of $\sigma = 20 \times \sqrt{\langle N \rangle / m} = 6.32$. If the true value of N is 200, our estimate N_E should fall within the range $200 \pm 2.33\sigma$, i.e. between 185 and 215, on 98 occasions out of 100, (and exceed 215 only 1 time in 100). Because of this spread in the possible values of N_E, if the true number were $N = N_0 = 200$, the estimate would exceed the limit N_0 half of the time, and a value of N_E slightly in excess of N_0 could not be taken as a reliable indication that there had been a violation.

A practical criterion for coming to a decision regarding verification might be to declare $N_c = 215$ as a critical "alarm level", and conclude that if the estimated number equals or exceeds this level (i.e. $N_E \geq N_c = 215$), then there must be more than the agreed number (i.e. $N > 200$), so that there has been a violation.

The probability that this inference would be wrong (i.e. that $N \leq 200$ even though $N_E \geq N_c = 215$, and that a false alarm had been signalled) would be $\alpha = 1\%$.

The higher the alarm level N_c is made, the smaller is the probability α of an alarm being false. But there is a disadvantage in increasing N_c, since if the actual number N of missiles is slightly above 200 (thus representing a small violation of the agreed limit $N_0 = 200$), the estimated number N_E may still be below N_c, and the violation would not be recognized.

If the actual number N of missiles is less than N_c, then the probability that $N_E \geq N_c$ is less than 50%, so that the violation would usually go undetected. If $N = 225$, there would be a probability of $\beta = 7\%$ that $N_E < N_c = 215$, so that a violation to the extent of 25 extra missiles would escape detection. In order that the probability of failure to detect a violation fall below $\beta = 1\%$, the actual number N of missiles would have to exceed 230.

To summarize the decision rules and the four possible outcomes:

If $N \leq N_0$, the inspected party is complying with the treaty;

If $N_E < N_c$, the inspector will (correctly) infer compliance

If $N_E \geq N_c$, the inspector will (incorrectly) infer that there has been a violation

- this outcome has (a false alarm) probability α
- we want α to be small
- α becomes smaller
  - as N decreases
    - i.e. fewer missiles
  - or as N_c increases
    - i.e. a higher threshold N_c

If $N > N_o$, the inspected party is violating the treaty

If $N_E \geq N_c$ the inspector (correctly) infers a violation

If $N_E < N_c$ the inspector (incorrectly) infers compliance

- this outcome has a probability of failure to detect β
- we want β to be small
- if $N_o < N < N_c$, then β exceeds 50%
  - probability of correctly inferring a violation is $(1-\beta)$
  - we want $(1-\beta)$ to be close to 1.00
  - more missiles (in excess of N_o), or a lower threshold N_c increases the probability of detecting an actual violation.

As the number of days m of observation increases, α and β both decrease. Or, the alarm threshold N_c can be reduced to leave α unchanged and reduce β even more.

It is possible to calculate a level of violation, expressed as an excess $(N-N_o)$ above the permitted number of weapons N_o, which will almost certainly result in detection, and with very low chance of a false alarm. It depends on N_o, the sampling density S, the period of surveillance m, and the levels set for probability α of a false alarm and β of the failure to detect.

Detecting a Breakout

Suppose that the inspected party has kept $N \leq N_o$, i.e. complied with the agreement, for a considerable time, but then suddenly deployed additional missiles to bring the total up to a number $N > N_o$, which would constitute a violation.

Suppose that the permitted level is $N_o = 200$, and that a new set of observations commences, with the alarm threshold N_c being chosent to make the false alarm probability $\alpha = 1\%$. With a sampling density of 5% per day, the threshold level N_c which would give a confidence level of 99% that $N > N_o$ if $N_E \geq N_c$ could be reduced with time as shown below:

Number of days of observation m :	1	5	30	100
Alarm Threshold N_c to make α = 1% :	348	266	227	215

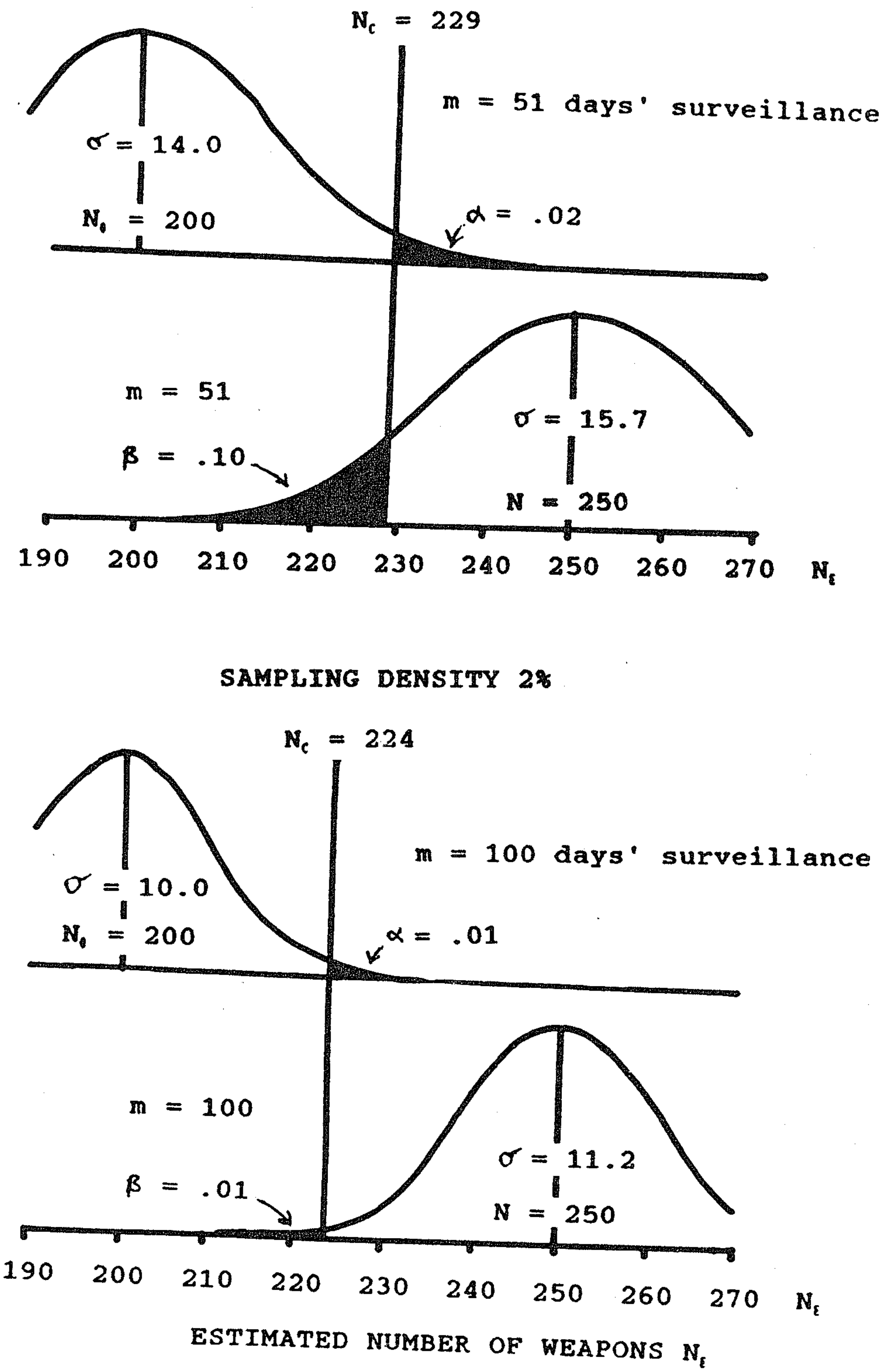
Figure I shows the probability distributions for the estimated numbers of missiles N_E when the actual number N is 200 and when it is 250. The upper pair of curves represent 51 days' observation with a sampling density of 2%. If the alarm threshold N_c is set at 229 the false alarm probability α will be 2%. If the true N is 250, there will be a probability β of 10% of having $N_E < 229$, in which case the violation will not be inferred. But if the number of days of observation (m) is extended to 100, the lower pair of curves show that the alarm threshold N_c can be reduced to 224, giving a false alarm probability α of 1%, and now the probability β of failing to infer a violation (when it is actually by 50 weapons) will be reduced to 1%.

Figure II shows the dependence of the alarm level N_c on the duration of the surveillance, m days, assuming that the agreed limit is N_o = 200, the sampling density is 5%, and N_c is calculated to give a false alarm probability of α = 1%. Also shown is the actual number or weapons N for which the probability is 99% that the estimated number N_E equals or exceeds the threshold N_c.

For example, after 20 days the threshold N_c would be set at 233. If the estimated number N_E equals or exceeds 233, the conclusion that the actual number N exceeds 200 would be a false alarm only once in 100 occasions. But if N is between 200 and 232, there is a probability of less than 50% that N_E will exceed 233, i.e. that the violation will be inferred. For the probability of correctly inferring a violation to be as high as 99% it would be necessary for the real number N to be 271 or more. But surveillance extending over 100 days would allow a threshold N_c of 215 to keep the false alarm rate at 1%, and to give a 99% probability of signalling a violation at the level of 231 weapons. It can be seen that the capability of the system improves rapidly during the first 50 days, but comparatively slowly thereafter.

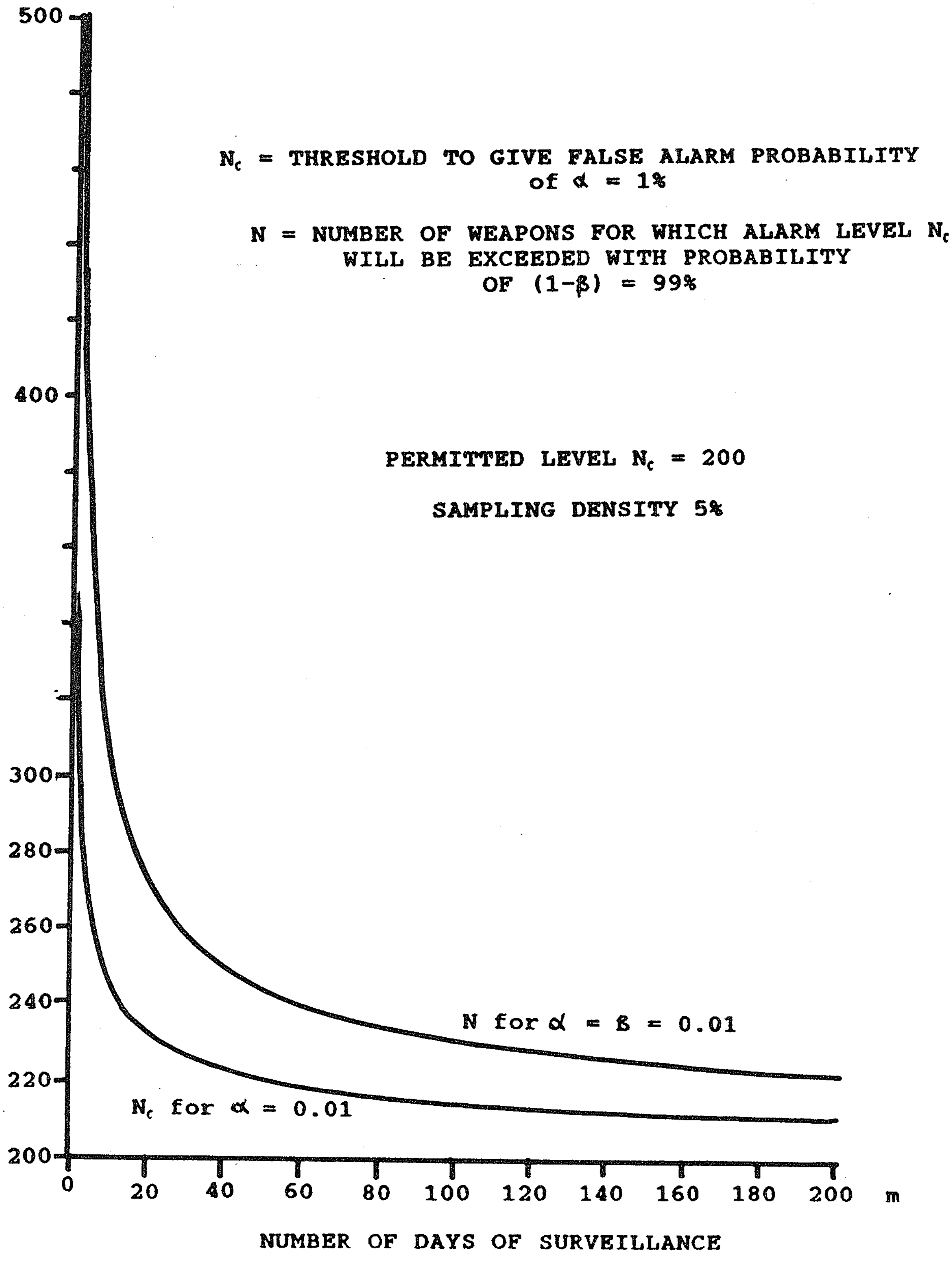
Finally, Figure III shows the probability (1-β) that $N \geq N_c$ (i.e. that a violation will be inferred), plotted against the actual number N of weapons deployed, calculated for an agreed limit N_o of 200, a sampling ratio of 5%, and with N_c set for a false alarm level α of 1%. The curves represent observation periods of 2, 3, 5, 10, 30, and 100 days. Looking along the horizontal line at (1-β) = 90% it is seen that if it were felt that a 90% probability was adequate to infer a violation, then it would take 10 days before a deployment of 277 weapons would cause a violation to be inferred with adequate confidence, 30 days for 243, and 100 days for 223. If 99% confidence were demanded then the deployment levels after 10, 30, and 100 days would need to exceed 304, 258, and 231 respectively, and 5 days would be insufficient to detect with such high confidence any levels below about 400. This illustrates the fact that while a large breakout should be detected in a short time, it will require a much longer period of observation to infer the occurrence of a small violation.

When all the mathematical analysis has been done, it is still necessary to apply subjective human judgement regarding the degree of confidence required to make conclusions, to assess the seriousness of various levels of non-compliance, and do decide whether to charge the inspected party with a violation.



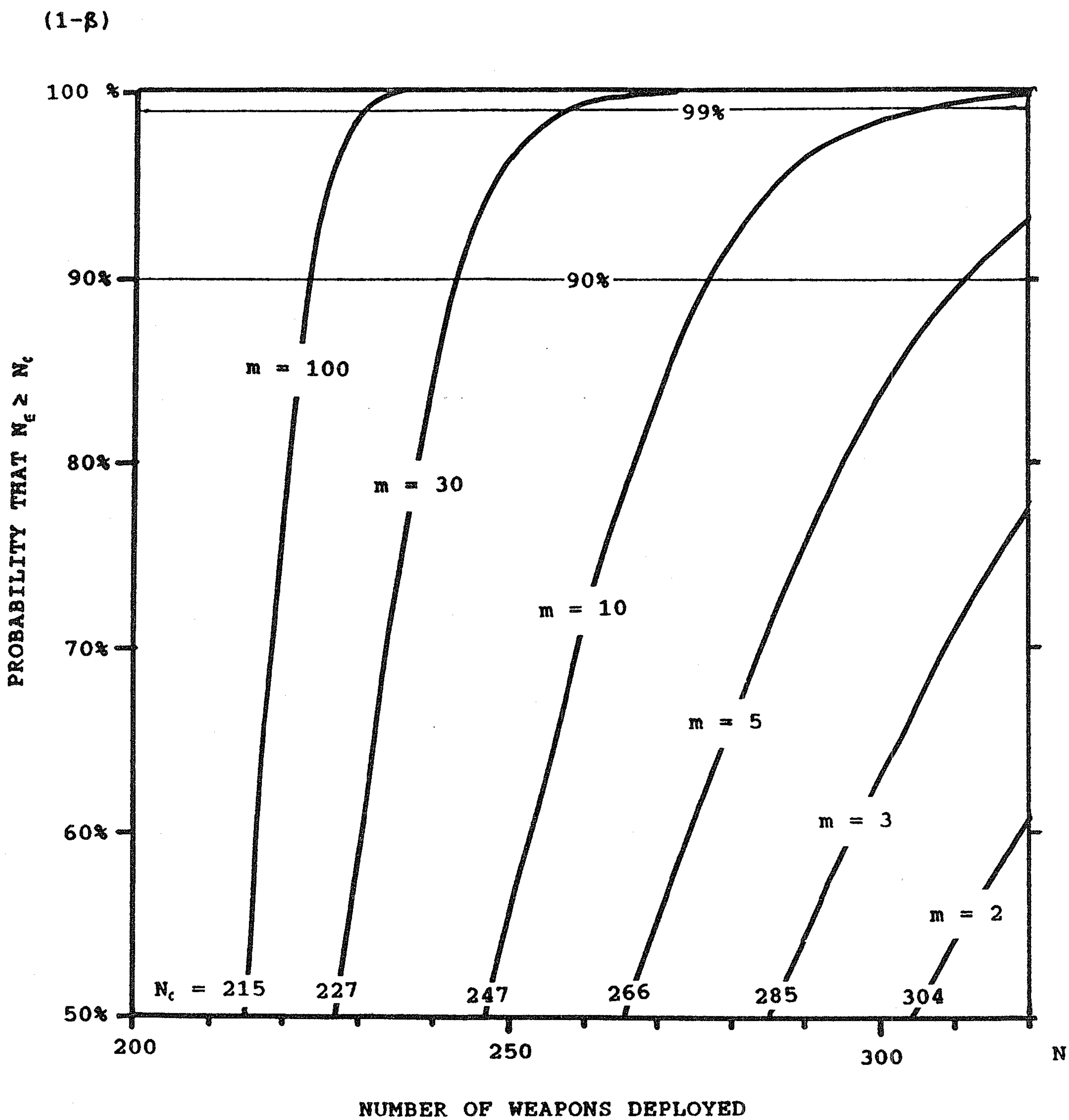
THE SHRINKING OF α AND β AS MORE OBSERVATIONS ACCUMULATE

FIGURE I



N_c = THRESHOLD TO GIVE FALSE ALARM PROBABILITY of α = 1%
N = NUMBER OF WEAPONS FOR WHICH ALARM LEVEL N_c WILL BE EXCEEDED WITH PROBABILITY OF $(1-\beta)$ = 99%
PERMITTED LEVEL N_c = 200
SAMPLING DENSITY 5%
N for $\alpha = \beta = 0.01$
N_c for $\alpha = 0.01$
500
400
300
280
260
240
220
200
0
20
40
60
80
100
120
140
160
180
200
m
NUMBER OF DAYS OF SURVEILLANCE

FIGURE II



$N_0 = 200$ $\alpha = 0.01$ $S = 5\%$

FIGURE III
THE PROBABILITY THAT A THRESHOLD SET FOR A FALSE ALARM PROBABILITY OF 1% WILL BE REACHED IF N WEAPONS ARE ACTUALLY DEPLOYED