TEST BAN VERIFICATION MATTERS

Satellite Detection

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TEST BAN VERIFICATION MATTERS: SATELLITE DETECTION

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Executive Summary

Negotiations on a Comprehensive Test Ban Treaty (CTBT) are currently being held at the Conference on Disarmament in Geneva.

- Although not among the *primary* technologies for verifying a CTBT, satellite data will be useful in identifying test sites, and in locating and detecting the occurrence of nuclear explosions.
- Satellite images with sufficient resolution can show that preparations for a test are underway. Satellite images can also add extra evidence to anomalous seismic or radioactive events suggesting that a test has occurred. In both cases, such images would show the precise zone in which an on-site inspection (OSI) could be conducted.
- To date, only China has proposed that the verification regime should include a CTBT-specific satellite. However, such a satellite would not be cost-effective.
- Countries will be free to check on the implementation of a CTBT with their own National Technical Means (NTM) and to share that information. However, this type of information will not be equally accessible to every country and it may also be suspected of politically-biased interpretation.
- When countries do not have such data available, commercial satellites could provide further reliable information. Images from commercial satellites can be bought by anyone. Such images present a poorer resolution, but can to some extent prove useful for CTBT verification. By the end of the decade, the appearance of higher resolution commercial satellites will decrease the distinction between commercial and classified images.
- The Implementing Authority for a CTBT could seek to supplement NTM information with independently obtained data. A Satellite Data Centre within its International Data Centre could establish a library with raw data available from commercial satellites and process and analyse these data. Raw data could be consulted by countries without space capability, and analysis on particular cases could be provided to countries without interpretation capability. If it can be provided with enough independence, the Centre would give the most impartial interpretation of raw data that can be expected and would actually resolve the problem of equal and universal access to satellite verification means.

The importance of satellite data for a Comprehensive Test Ban Treaty

Satellite images are not at the core of a CTBT verification regime, but present some specific advantages

Negotiations at the Conference on Disarmament place an international seismic monitoring system at the core of the CTBT verification regime. This seismic network will be supplemented by an international radionuclide monitoring network and possibly a hydroacoustic network. The role of shockwave detectors, satellite observation, optical flash detection (i.e. bhangmeters) and electromagnetic pulse monitoring have yet to be determined.[1]

Data from satellite images have a useful role to play:

1. They can provide evidence that preparations for a test are underway, providing advance warning of a potential violation;

2. They can provide more precise information on the location of test sites. Whereas seismic means at best narrow the location of a test down to a few kilometres, satellite pictures can pin-point the epicentre, thus allowing more efficient on-site inspection (OSI);

3. Satellite images also have a strong impact on public opinion when published in newspapers or shown on television, and this political impact should not be underestimated. Compared with other verification means, satellites produce actual pictures of the test sites. The typical before/after pictures of a test facility, when used as visual proof, have more impact on public opinion than, for example, abstract seismic monitoring signals. Apart from particular sanctions that a CTBT may endorse, international public condemnation of a rogue state can be fostered more easily by satellite evidence. Such a process could enhance the effectiveness of a verification regime, should a breach of the treaty be detected, and should these results made public.

This paper examines the following questions:

- What is the technical use of a commercial satellite image for the verification of a CTBT? How does it compare with very high resolution military means?
- What is the availability of the different satellite data?
- Is a biased interpretation of satellite data avoidable, and if so who qualifies best for carrying out objective interpretation?

Satellite imagery in the process of CTBT verification

Satellite data would be useful for verifying a CTBT as part of a broader pattern of verification means including a seismic network, other non-seismic means, and on-site inspections.

1. The Arms Control Reporter, *608-B-295, Institute for Defense & Disarmament Studies, Cambridge Massachusetts, 1994.*

In arms control treaties, such as the Intermediate-range Nuclear Forces treaty (INF) or the Strategic Arms Reduction Talks (START), satellite data come chronologically first in the process of verification: satellites scan large portions of territories, and on-site inspections are the final and decisive tools of investigation.

This contrasts with treaties involving underground and surface nuclear tests whether 'civilian' (1976 Peaceful Nuclear Explosions Treaty) or military (1974 Threshold Test Ban Treaty), where the interest focuses on explosions. Verification of compliance with such treaties relies more heavily on seismic detection, supplemented by other means.

A nuclear test ban treaty verification regime would follow successive steps, with a particular place for each technology.

Firstly, the process is different according to whether the test has occurred (in which case the Implementing Authority (IA) is only checking its suspicions that a test has really occurred), or whether the test has not yet taken place (in which case the IA is looking for evidence that a state is currently preparing for a test). This would be relevant whether or not a CTBT bans preparations in the basic obligations.

Before a test

Satellite images are an efficient way to spot preparations for a nuclear test

Different information sources would bring suspicion that a state is preparing a nuclear test (there are approximately 7 known sites in the nuclear-weapon states (NWS), and about 10 threshold countries which might have one or more potential test ranges).[2] Even though preparations may not be specifically referred to in the treaty, routine monitoring by satellites would help the IA focus ahead on potential areas of concern. The IA and scientists could be on their guard for unusual seismic events from potential test-sites identified by satellite.

Overhead images would constitute primary evidence that a test is under preparation (roads and perimeter fences, drilling, mass of extracted soil, etc.). Such evidence should lead to the alert of all other (seismic and non-seismic) verification means, and, should an event occur, trigger the immediate request of an on-site inspection.

> **Successive steps:** information ⇨ satellite scanning ⇨ seismic and non-seismic means alert & on-site inspection request.

Preparations for a nuclear test may not be forbidden by a CTBT

Preparations for a nuclear test will probably not be explicitly forbidden in the text of a CTBT and on-site inspections will probably not take place on the grounds that preparations are suspected in a particular country. Deterrence of would-be violators will nevertheless be an aim of the treaty and early monitoring of suspicious states will be useful. Satellite images would, in that case, be the only means at hand to indicate that preparations are underway.[3]

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2. *See Appendix E, p. 23.*
3. *Rebecca Johnson and Sean Howard,* A Comprehensive Test Ban Within Reach, *Acronym Booklet No 1, May 1994, p. 6.*

After a test

Satellite images can show where the test has occurred

A seismic shock detected by seismic and non-seismic means would indicate that a suspected nuclear test has occurred in a particular region, but the region would be quite large in area.[4] Satellite images would help scan the territory and could see the exact place where the test might have occurred, thus defining the area necessary for an OSI.

If the IA is to monitor implementation of a CTBT through a global network, threshold countries will be paid particular attention, even if they are not parties to the treaty. Continuous surveillance of potential test-sites would be part of the international community's monitoring strategy. There would therefore be a reduced risk of the world being surprised by a sudden test.

> Successive steps: detection of seismic shock by seismic and non-seismic networks ⇨ satellite scanning ⇨ on-site inspection request.

Interpretation and subjectivity

Raw data, processed image, interpretation

Interpretation of satellite images is an important issue. Satellites produce raw data. Processing of the data produces images on which particular objects such as roads, buildings, mine shafts, etc., can be detected and identified. However, because the utility of these objects cannot always be determined by the images alone, this type of information must be correlated with other information on the country or the area. This is the process of interpretation. Interpretation is highly dependent on the photo-interpreter(s) deciding on the nature of what is visible on the picture and is therefore (as are all analytical processes) a subjective process. The interpreter can try to remain impartial in the interpretation, or be influenced by political views.

Interpretation is subject to political bias, especially with NTM data

Interpretation of NTM is particularly vulnerable to political bias because it takes place in a national institution which is structured within a national perspective, and the actual pictures cannot generally be shown in an international forum. Also, whereas low resolution in commercial satellite images may only indicate the possibility of anomalous events, leading to questioning comments, the more precise NTM images may allow interpreters to make definitive rather than questioning assertions, which could then be politically disruptive.

An international body working on commercial data may be more objective

Although political bias cannot be totally averted, interpretation of data by international bodies could be less vulnerable to such bias and therefore to external suspicion of such bias. Raw data available for interpretation by an international body would be almost exclusively of commercial origin.

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4. See Appendix E, p. 29. Teleseismic arrays cannot locate the epicentre better than a few kilometres.

Satellite data and OSI decision making

There are risks involved with taking satellite data and its analysis into account when making a decision on an OSI. Much depends on the way OSI decisions will be made within the CTBT implementation structures. To aid discussion, three possible scenarios for decision making are discussed below. There are, of course, several permutations of these decision-making scenarios. However, for reasons of clarity, only the three main approaches are considered here.

OSI decision making

Many elements in the following discussion would also apply to other sorts of data relevant to the CTBT verification regime. However, as seismic and radionuclide networks will almost certainly be part of the verification regime, there is no point in submitting them to such specific discussion.[5] Therefore, only satellite data is discussed here, with the understanding that many points raised apply to other data gathering and analysis processes.

Scenario 1: The receiving country decides whether or not to accept an OSI

In this first scenario,[6] an accused state would be confronted with evidence gathered by an accusing state, and asked to accept the OSI or justify its refusal. Such a process would almost certainly lead to tension and the lining up of allied countries. There are several possible variations to consider with regard to the data at hand in such a situation:

A. If the accused country does not have its own verification means and the IA has its own data centre, the accused country could be provided with independent data to justify whatever decision it makes regarding the OSI request.

B. If the accused country does not have its own verification means and the IA does not have any data available, then information provided both by the accusing state and by other countries could be available, but such information could well be contradictory or ambiguous and may not engender objective debate.

C. If the accused country has some national verification means and the IA has its own Data Centre, the IA could provide more objective information, should an irreconcilable dispute over data interpretation arise between the two countries and their allies.

D. If the accused country has some national verification means but the IA does not have any data available, a dispute could arise over each country's data and interpretation. Information provided by other countries would only be useful if it appeared to be less questionable than the information provided by either of the protagonist states.

5. *Hydroacoustic verification is the subject of a forthcoming* Test BanVerification Matters *issue.*
6. *This scenario is based on the 1983 Swedish Proposal to the CTBT negotiations:* Swedish Draft Treaty banning any nuclear weapon test explosion in any environment, *CD/381*, 14 June 1983, Protocol 1:* International co-operative measures to facilitate the verification of a Treaty banning any nuclear weapon test in any environment.

Information provided by an impartial body could introduce more objectivity in the debate

Whether the accused country has its own satellite means or not, the only way a dispute over the alleged evidence can be avoided is by providing some sort of objective or seemingly objective interpretation of the data. Whereas third country information may not avoid political bias, an International Data Centre within the CTBT's IA could be a more impartial tool, if it is given sufficient independence.

Scenario 2: The IA decides whether or not to conduct the OSI

The 1993 Swedish proposal refers explicitly to the International Atomic Energy Agency (IAEA), giving its Board of Governors the responsibility to decide whether or not to conduct an OSI, by a two-third majority vote.[7] Although the Statute of the IAEA indicates that countries on the Board are geographically and politically represented, and are expected to discharge their function without political bias, this is a controversial matter. [8]

Also, since the IAEA's Board of Governors would not have the same membership as a CTBT, its legitimacy to monitor a CTBT is questionable. This argument is used as another incentive to limit the IA's role to technical analysis of data. However, the IAEA is already monitoring the Non Proliferation Treaty (NPT) which does not have the same membership as the IAEA Board of Governors.

IA likely to have some degree of collaboration with the IAEA

The financial cost of monitoring a CTBT would be reduced if the IAEA was chosen to perform that task. If the negotiators in Geneva decide to create a self-standing Implementing Authority for a CTBT, it seems likely that some sort of collaboration between the IAEA and this IA will be adopted.

The IAEA has very limited experience with satellite imagery to date,[9] but could become experienced over a short period of time. OSI decisions could then be made on information derived from independent means and subjected to "impartial" interpretation.

Although interpretation of data cannot be completely objective, the most obvious political biases can be averted and the most impartial interpretation can be expected if the process takes place in a non-national and independent forum. However, it can be argued that because the interpretation of data and facts cannot completely escape some sort of political bias, it should then remain in the hands of the States Parties, so that biases in the presented interpretation are at least known and obvious to all States Parties. The multiplication of sources would then become the guarantee of an informed debate.

If the IA makes the decision on an OSI, it needs its own information system

The negotiators also need to decide if the IA can be given an extensive role where satellite data treatment is concerned. Only when the kind of information available within the IA is known, can the IA's role in OSI determination be asserted.

If the treaty gives the IA the power to decide on an OSI but does not give it the means to gather, analyse and interpret the data independently, the IA would not be able to carry out its function properly.

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7. *This scenario is based on the 1993 Swedish Proposal to the CTBT negotiations:* Letter dated 6 December 1993 from the Head of the Delegation of Sweden addressed to the Secretary-General of the Conference on Disarmament transmitting the text of a Draft comprehensive nuclear test ban Treaty and its annexed Draft Protocol, *CD/1232, CD/CTB/WP 33, 6 December 1993.*

8. *See Appendix D.*

9. *Interview with Bhupendra Jasani, 1 June, 1994.*

If the IA not only has the power to decide on an OSI request by a State Party, but also can initiate the OSI,[10] the basis of such a decision would be under the same terms as above.

Scenario 3: An automatic OSI follows a State Party's request

There would be no decision to be made by anyone in the case where the request of an OSI by a State Party is followed by a compulsory OSI.[11] However, as in the other scenarios, the OSI would be conducted by the IA. It would therefore have to make the decisions on how, when and where to carry it out. The requesting country would point to a particular place where the OSI had to be conducted in the accused country, but the IA-conducted delegation would choose the particular facilities and zones that it wanted to inspect. Information would therefore also be necessary in that scenario.

The OSI team would need its own information

If the IA does not have its own data and interpretation means, it will rely on information provided by the requesting country, possibly by the accused country, and also by other countries. The quality and objectivity of such information cannot be assessed in advance. The inspecting team having access to second-hand information only does not seem to be a very efficient way of conducting an inspection.

If the IA has its own data and information means, the inspecting team will be able to conduct the inspection with more confidence.

The IA would need information to detect abusive OSI requests

It is almost certain that some requests for an OSI will be called abusive by the accused country or by other States Parties. If the treaty provides against such abuses, the IA will again have to judge on the validity of satellite information provided by the requesting country and friendly countries. It will in that case need some knowledge of that kind of data. The Chemical Weapons Convention has established a system of OSI requests with a provision against abusive requests. The permanent Executive Council can veto a request by a majority of three quarters in the 12 hours following the request.[12]

If the treaty does not specify such provisions, and a request by a state will be enough for an OSI to be conducted, this will specifically allow political bias to govern the verification regime.

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10. There is discussion around the 1983 and the 1993 Swedish Proposals on the possibility that the Executive Council within the IA could actually initiate an OSI, without any request by a State Party.

11. This scenario is based on the 1991 Swedish Proposal and the 1994 Australian Draft presented to the CTBT negotiations and has parallels with the Chemical Weapons Convention. See Letter dated 9 July 1991 from the Head of the Swedish Delegation addressed to the Secretary-General of the Conference on Disarmament transmitting the text of a Draft Comprehensive Treaty and its annexed Protocls, *CD/1089, CD/NTB/WP, 14, 31 July 1991, and* Comprehensive Test Ban Treaty, Australian Resource Paper on Draft Treaty Elements, *CD/NTB/WP, 49, 30 March 1994.*

12. Chemical Weapons Convention, article 9, paragraph 17.

NTM and/or commercial images?

Comparison between NTM and commercial satellite data — technical and political considerations.

Technical considerations	NTM	Commercial
Availability:		
Cost	Could be free to the IA although there may be some form of repayment if a large number of images are supplied	Approximately US$ 3,000* per image
Readiness	No control over when the images could be available	Some control but service can be made unavailable at short notice
Ownership	Temporary inspection	Would belong to the IDC
Quality:		
Resolution	Very good for observation of preparations for a test, for example drilling, traffic movements, etc. Not good for large-range spectral coverage	Good multispectral sensors for post-test signals such as changes in vegetation and soil Generally not good enough for optical observation of preparations Commercial capability is likely to improve by the end of the decade †
Coverage	No control	Some control, but some areas have been politically or technically unavailable
Political considerations		
Credibility	Suspicion of political bias by other countries	Questions on interpretation of low resolution images
Cooperation in times of crisis	Depends on the leanings of the country operating the satellite	Prime motivation is commercial but could be restricted by government policy

*Current price of a Spot image with a basic correction, see Appendix E, p. 31.

†See Appendix C.

In 2-3 years, commercial images with an improved resolution (≤ 2 m) should be on the market

The current choice is between independent means with a resolution poorer than 5 metres (average commercial data) or data with a resolution better than 50 centimetres, but with no free access and possible political restriction (NTM). In a few years, commercial satellites with a two metres resolution should be available.[13] China has advocated a CTBT-specific satellite that would have the resolution of current commercial satellites, but this is viewed by other states as too expensive and unnecessary.[14]

Questions on the structure and role of the IA

Political bias in the interpretation process

The question of which sort of data should be sought by the IA depends on the role it would have with regard to the analysis of the data. Sweden brought the issue to a head in early June, differentiating between analysis – which should be the role of the IA – and interpretation – which should belong to the States Parties – because of the political judgements that are involved in the interpretation of data.[15] Other states have raised their concern that those with less advanced technology may get squeezed out of decision making, unless provided with some analysis from the IA. The distinction between analysis and interpretation may however be difficult to define in practice.

The IA could set up a Satellite Data Centre

In any case, the Satellite Data Centre set up by the IA would purchase raw data devoid of any political bias. The processing of these images would also be a scientific process. Only the last-phase interpretation is subject to debate.

The majority view on the IA in Geneva is that it would include a Conference of States Parties, an Executive Council, and a Technical Secretariat of which the International Data Centre would be an integral part. If such powers are attributed to the IA, analysis of the data could lie with the Technical Secretariat and the IDC; decision making on OSI could be a role for the Executive Council and, if necessary, the Conference of States Parties. The technical/political attributions that will be given to each of these bodies is of particular importance for the way in which the verification regime will operate.

The next section looks at different alternatives such as whether or not the IA should receive satellite data centrally.

Scenario 1: The Implementing Authority (IA) does not receive satellite data

The task of verifying compliance lies with the States Parties.[16] They would get satellite data either from their own or other countries' national systems, or from commercially operated systems.

13. *See Appendix C.*

14. *Rebecca Johnson and Sean Howard, op. cit., p. 14.*

15. *See speech by Ambassador Lars Norberg, 2 June 1994, Ad Hoc Committee on a Nuclear Test-Ban, Working Group on Verification, Sweden,* Comments on International Data Centre, Analysis and Products, *6 June 1994, and* Nuclear Proliferation News, *Volume 94, No. 5, 1994, p. 3.*

16. *This scenario is based on the 1983 Swedish Proposal to the CTBT negotiations, op. cit.*

In the former case, as very few countries have space observation means, most would depend on countries with observation capabilities to share information with friendly countries (possibly along the line of the CD political groupings[17]):

– The group of Western countries and perhaps some Eastern European countries could get data, or at least information, from the US or the European countries operating Hélios.

– The Group of 21 could be informed by India or Brazil (Brazil does not yet have space observation capabilities, but has been looking into the possibility of developing such capacities[18]). They may also get information from China which does not officially belong to any political grouping but has good relations with the G21 States.

– The group of Eastern European countries and other states could potentially receive satellite data from Russia, but this would depend on the development of political relations.

Countries without space capacities would rely on information provided by allies

Some countries relying solely on NTM data from other countries would not have access to the real images, but only to information derived from the processed images, or to images with a degraded resolution. When American concern grew about North Korean nuclear activities, US intelligence officials shared their fears with the IAEA by showing satellite evidence, but they did not leave the images with the IAEA. This led to some difficulties in the following discussions between the IAEA and the North Korean government. The latter would not discuss accusations based on satellite data unless shown the actual images, otherwise it was treated as second-hand information or as hearsay. During the 1991 Gulf War, the fact that US intelligence provided derived information and not actual data to most countries in the Coalition caused dissatisfaction to countries such as France. Such problems also occur within NATO: information derived from US NTM is used without disclosure of actual data, which arouses political sensitivities, particularly as some countries have access to raw data and others do not. There is a risk of conflict within the different groups, unless the terms and conditions of the access are clearly defined and agreed beforehand.

They could also buy data from commercial agencies

The other solution for countries without space observation capabilities, whether belonging to a negotiating group or not (the latter including sensitive nuclear capable or threshold states such as Libya, Iraq, Israel, Taiwan, North Korea, South Korea and South Africa[19]), would be to buy satellite data directly from commercial agencies. Spot-Image has an official policy of "open skies – open access" and is ready to sell any picture to anybody for the price of approximately US$ 3,000.[20] However, this openness can be reduced for political and/or technical reasons in times of crisis, as the Gulf War experience showed.[21]

Analysis skills would be required

Analysis skills would be needed to interpret the data. Quite a number of countries without satellite systems have trained photo-interpreters. This is often because they have been developing similar basic skills through interpretation of aerial images. Many

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17. *See Appendix A.*

18. *See Appendix C.*

19. *See Appendix B.*

20. *Current price of a first-degree correction Spot-Image, see Appendix E, p. 31.*

21. *P. D. Zimmerman, "The Use of Civil Remote Sensing Satellites During the 1990-1991 Gulf War, in* Verification Report 1992, *VERTIC, London, 1992, pp. 230-233.*

countries have done aerial reconnaissance for a long time and the Open Skies Treaty will widen the use of this technique. Also, in the East-West context, on several occasions, the US and USSR gave images to allied countries such as South Africa, South Korea, Israel, Taiwan, Egypt, Iraq and Libya.[22] Even if these countries do not have their own observation capacities by now, they are accustomed to satellite images and possess some analytical capability. Many countries started to develop such skills in the 1970s. Egypt set up a processing centre for Landsat and Spot in the early 1970s; Thailand did the same for Landsat in 1983; and Kenya has 200 trained photo-interpreters belonging to the African Remote Sensing Council.[23]

Problems of availability

However, states could not be certain they would get the image they want rapidly. Different commercial agencies claim they can obtain and sell recent images from a catalogue of different locations fairly quickly. When put to the test, this could prove to be less efficient. Whether for technical or political reasons, it proved impossible for independent researchers to obtain recent images of the Chinese nuclear test-range, either from Russia, Landsat or Spot, in 1993.[24] In the years to come, new satellite-operating companies may sell rights of exclusivity to ground stations over a particular area. It may then become possible for a country embarking on a covert nuclear test programme to gain control of the ground station covering the concerned area, thus depriving anybody else from access to satellite images of that area.[25]

NTM and commercial data can be complementary

If, as we have seen, NTM images cannot generally be used in the international debate, interested parties can nonetheless try to buy commercial images of the same location and use them as evidence. This is what British delegates did when visiting the Soviet Chemical Weapons Research Station at Shikhany. Having spotted another facility linked to the Research Station, probably with NTM, they showed Landsat commercial pictures depicting the facility, and asked to be taken there. Although the request was refused, this proved that commercial pictures could replace high resolution data in an international discussion.[26] Classified and commercial images prove to be complementary.

In a confrontational situation, it is likely that the evidence on which the states based their accusations or concerns would be questioned. For example, if a state was to accuse another of having conducted a test using evidence from satellite images, it would probably not show the actual images. The accused state and its allies would then be left free to deny the validity of the evidence, or come up with contradicting images. However, they could use commercial images in lieu of NTM data as above.

22. *Louis J. Levy and Susan B. Chodakewitz, "The Commercialisation of Satellite Imagery, Implications for Cross-Border Conflict"*, Space Policy, *August 1990, pp. 210-220.*

23. *See Appendix C.*

24. *Vipin Gupta and Philip McNab, "Sleuthing from Home"*, Bulletin of the Atomic Scientists, *December 1993, pp. 44-47.*

25. *See Appendix E, p. 28.*

26. Statement on the Defence Estimates 1989, *Vol. 1, Cm 675, Mat 1989, Her Majesty's Stationery Office, 1989, London, pp. 9-10.*

Scenario 2: The IA receives data

A Satellite Data Centre

In this scenario,[27] the IA could have the task of centralising raw data, analyse and interpret it. The IA may then set up a Satellite Data Centre (SDC) as part of an International Data Centre.[28] The Centre would get its data from two sources: national systems and commercial systems.

From States Parties operating satellite systems

Countries operating an unclassified satellite system could provide relevant data to the Centre.[29] There are also European systems such as the European Remote-sensing Satellite (ERS) system that could be of use. The Centre could do its own analysis of these raw data.

An SDC would get information derived from NTM

If it would be in their interest, states could also provide NTM data. The question would arise whether the Centre would be allowed access to raw NTM pictures. If it is only provided with the result of NTM analysis by the countries undertaking verification on their own account, this might not be regarded as adequate by other States Parties and the Centre would have to take the possible biases in interpretation into account.

From commercial agencies

The core of the IA satellite data would consist of images from commercial agencies. As an important treaty verification unit, the Centre may have more financial means and international prestige than a single state or private organization to buy or obtain useful images. It would therefore be able to gather an effective amount of pictures and analysis, thus establishing a consistent library of images. Studies show that the financial means required remain reasonable.[30]

An SDC could provide an extensive library of raw data

The study presented in Appendix E indicates that analysis of raw commercial satellite pictures of the major suspicious areas would require approximately 30 photo-interpreters working in teams of two. They would need work-stations, i.e. special analysis computers, but would do some of their work off-line (researching in the Centre's library, studying and comparing photographs, etc). They would also need output devices, such as printers.[31]

Copyright issues

For questions of copyright, raw data bought by the IA would not be duplicable, unless royalties are paid by the IA to the seller or a particular deal is reached between them. Analysis and processed images derived from the raw data by the IA may however be freely communicated. Raw data may also be consulted by States Parties on the IA premises.[32]

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27. This scenario is based on the 1991 and 1993 Swedish Proposals and the 1994 Australian Draft presented to the CTBT negotiations, op. cit.

28. 1991 Swedish Proposal, op. cit.

29. 1991 Swedish Proposal, op. cit., paragraph 3, p. 15.

30. See Appendix E, pp. 31-32, for an US$ estimate of the annual cost of a satellite observation centre (images, photo interpreters). The author concludes that "the base costs for operating a monitoring agency ... are remarkably affordable so long as the area to be studied is relatively small and can be defined in advance."

31. See Appendix E, pp. 32-34.

32. Telephone interview with Jeremy Stokes, from the National Remote Sensing Centre (United Kingdom), 29 September 1994.

The ISMA project

There is a chance that a Satellite Data Centre with an analysis task and independent means would resemble the International Satellite Monitoring Agency advocated by some experts (although in the first place it would be tasked only with the CTBT).[33] Providing certain conditions are met, the Centre could be sufficiently impartial and effective. Included in such conditions should be the establishment of a degree of independence by:

- some limited financial means,
- a long term mandate,
- a geographically and politically representative staff,[34] and
- a location in a neutral country such as Austria or Switzerland.

The WEU Space Centre

It should also be put into use by the Implementing Authority and the States Parties very quickly, and that use should become common. From this point of view, the Western European Union (WEU) Satellite Centre's experience is interesting. The Centre was officially created at the beginning of 1993, but started to operate in April, 1994. It had a very slow up-take, for none of the WEU Member States were really interested in or aware of the uses the Centre could be put to. Countries have now started to use the Centre, allowing it to develop a proper analysis know-how and gain a reputation among the verification specialists within WEU countries. This tends to show that international analysis centres do function best when their use by the funding countries as a whole is common and frequent.[35]

Since their surveillance expertise would be similar, a synergy could be developed between the WEU Satellite Centre and a CTBT Satellite Data Centre. It has also been suggested that the European Space Agency (ESA) could be part of such a collaboration.[36] Because these two organizations are European, careful structuring and monitoring would be needed in order to reduce the risks of introducing further political biases into a CTBT monitoring.

33. *Bhupendra Jasani, "ISMA, will it ever happen?",* Space Policy, *February 1992, pp. 380-383.*
34. *1993 Swedish Proposal, op. cit., and Appendix D.*
35. *Interview with Bhupendra Jasani, 3 August 1994.*
36. *Bhupendra Jasani, "Verification of arms reductions in Europe from Space",* Observation Satellites – European means of verifying disarmament, *WEU Symposium, Rome, 27-28 March 1990, p. 65 and p. 68.*

Conclusion & recommendations

Satellite observation as a verification tool brings accuracy and precision to the localisation of covert nuclear test sites. It is therefore useful and should be part of a comprehensive test ban treaty verification regime.

A small number of countries have military observation capabilities. Interpretation of these National Technical Means is subject to political bias and access of other countries to such data is very limited. This tool is therefore a limited one.

Commercial agencies sell images from observation satellites. There is no restriction to their access. Their resolution is poorer, but can still prove useful for security purposes. Moreover, in the years to come, satellites offering a two-metres resolution should be on the market.

The CTBT could try to supplement such data and organise a framework for the use of satellite imagery. This should be done with maximum guarantees of free access and political neutrality.

The Implementing Authority (IA) and its International Data Centre (IDC) could be provided with a Satellite Data Centre operating with sufficient impartiality. The Satellite Data Centre (SDC) would centralise, process and interpret raw satellite data from both NTM and commercial satellites as is available and appropriate. States Parties would have access to the raw data in the library set up by the SDC; they would be transmitted the processed images and the interpretation made by the SDC's photo-interpreters.

This could make impartial interpretation more likely and provide reliable information for the less technologically-advanced countries.

Such a Data Centre would enable the States Parties to make a more informed decision on whether, where and how to conduct an on-site inspection (OSI). When an OSI is requested, the IA could provide all parties deciding on the OSI with objective information. Such a framework would help to avoid disputes between two States Parties: the accused and the accusing states would be able to examine the evidence as analysed by the SDC. Opposition to OSI is more likely to arise if the accused state is deprived of satellite information, or if there is no reliable impartial analysis available in their discussion.

Although the raw data library would be useful in any case, it must be kept in mind that an SDC too obviously partial in its interpretation would be pointless. A SDC should be set up to make sure all states have an access to objective satellite information. If the SDC cannot meet this goal, the verification regime then would be better off relying on a few countries providing their own information and interpretation to the IA.

A final observation is that, should the International Atomic Energy Agency (IAEA) be involved in the CTBT verification regime, the fact that it would then use satellite imagery would have a beneficial effect on IAEA safeguards. Monitoring of nuclear proliferation could be enhanced with the help of space observation. The technical support brought by a CTBT-originated Space Data Centre to the IAEA would further increase the advantage of cost sharing.

Appendix A

Conference on Disarmament

Member States (37)

Algeria
Argentina
Australia
Belgium
Brazil
Bulgaria
Canada
China
Cuba
Egypt
Ethiopia
France
Germany
Hungary
India
Indonesia
Iran
Italy
Japan
Kenya
Mexico
Mongolia
Morocco
Myanmar
Netherlands
Nigeria
Pakistan
Peru
Poland
Romania
Russian Federation
Sri Lanka
Sweden
United Kingdom
United States
Venezuela
Zaïre

Non-Member States (47)

Austria
Bangladesh
Belarus
Cameroon
Chile
Colombia
Czech Republic
Democratic People's Republic of Korea
Denmark
Ecuador
Finland
Ghana
Greece
Holy See
Iraq
Ireland
Israel
Jordan
Kuwait
Libyan Arab Jamahiriya
Madagascar
Malaysia
Malta
New Zealand
Norway
Oman
Philippines
Portugal
Qatar
Republic of Korea
Senegal
Singapore
Slovakia
Slovenia
South Africa
Spain
Switzerland
Syrian Arab Republic
Tanzania
Thailand
Tunisia
The Former Yugoslav Republic of Macedonia
Turkey
Ukraine
United Arab Emirates
Vietnam
Zimbabwe

States proposed for acceptance as members ('O'Sullivan list') (23)

Proposed in August 1993 by Australian Ambassador Paul O'Sullivan, but blocked by the US because of the inclusion of Iraq, which revived Iran's opposition to Israel. It is possible that this list may be superseded by a proposal to admit all those states (about 33) which had applied for entry by a particular date.*

Austria
Bangladesh
Belarus
Cameroon
Chile
Colombia
Democratic People's Republic of Korea
Finland
Iraq
Israel
New Zealand
Norway
Republic of Korea
Senegal
Slovakia
South Africa
Spain
Switzerland
Syria
Turkey
Ukraine
Vietnam
Zimbabwe

* *Sean Howard and Rebecca Johnson*, Nuclear Proliferation News, *Vol 94, No 8, Dfax, Bradford, 5 August 1994*

Appendix B

States with Nuclear Research Reactors in Operation (November 1993) and/or Nuclear Power Reactors in Operation and under Construction (31 December 1993)

Algeria
Argentina
Austria
Australia
Bangladesh
Belgium
Bulgaria
Brazil
Canada
Chile
China
Colombia
Cuba
Czech Republic
Democratic People's Republic of Korea
Denmark
Egypt
Finland
France
Greece
Germany
Hungary
Indonesia
Israel
India
Iran
Italy
Jamaica
Japan
Kazakhstan
Latvia
Lithuania
Libya
Malaysia
Mexico
Netherlands
Norway
Pakistan
Peru
Philippines
Poland
Portugal
Republic of Korea
Romania
Russia
Slovak Republic
Slovenia
South Africa
Spain
Sweden
Switzerland
Thailand
Turkey
UK
Ukraine
USA
Uzbekistan
Venezuela
Vietnam
Yugoslavia
Zaire

Note: This list does not include Taiwan.

Appendix C

Non-exhaustive list of countries with space observation capability and space data interpretation skills

- NTM capacities today (resolution unknown, maybe less than 30 centimetres for optical sensors): Russia, US, China, French-Spanish-Italian consortium (Hélios satellite launched end of 1994 or beginning of 1995).

- Commercial systems (resolution 2 to 5 metres at best): Russia, US, France. The images produced by those satellites may be sold by commercial agencies in different countries. For instance, Russian intelligence satellite images, which are degraded for security purposes and still offer the best commercially-available resolution today (ground sample distance of 2 metres), are sold by commercial agents in Russia, Germany and the United States.[37]

  The world is however two or three years away from the start of a global proliferation of high resolution commercial satellites: South Africa is building a Greensat space observation system with a ground sample distance of 1.8–2.5 metres. Different American systems with resolutions between one and three metres are now under construction, following the March 1994 change of policy in the United States, which allows sale of one metre resolution images.[38]

- Some space observation systems are neither military, nor available on a commercial basis. The European Space Agency has launched several systems, such as the Earth Remote-sensing Satellite. Japan also has recently acquired space observation capabilities. India will launch a third remote-sensing satellite in the next 1–2 years. Israel might be launching a high resolution satellite by 2000. Brazil has mentioned the building of a satellite system for some years now, but nothing has materialised so far; so has Canada with the project Paxsat.[39]

- Many countries with no space capabilities have nonetheless developed data processing, analysis and interpretation skills. Commercial agencies in Japan, Sweden, India, Brazil and Kenya, for instance, are selling images produced by other countries' satellites and are providing interpretation as well. Third World countries have developed analytical facilities since the 1970s. Kenya, Zaire, Burkina-Faso, have had processing facilities since 1977. Argentina has had a receiving facility operating for Landsat, Spot and Tiros images since 1980. Thailand and Egypt have photo-interpreters in training centres working on Spot and Landsat data.

  Virtually every country now receives meteorological data from internationa satellite systems such as Eumetsat or Meteosat. They usually do their own analysis

37. *Vipin Gupta and Philip McNab, "Sleuthing from Home"*, Bulletin of the Atomic Scientists, *Decemb 1993, pp. 44-47.*

38. *Vipin Gupta, "New Satellite Images for Sale: The Opportunities and Risks Ahead"*, LLNL Repor *No. UCRL-ID-118140, 28 Septembre 1994, pp. 34.*

39. *Telephone interview with John Pike from the Federation of American Scientists (Washington, DC), 1 August 1994.*

The Philippines, Kenya and Indonesia, amongst others, also use satellite imagery for agricultural needs.

Many countries have gained image data interpretation know-how through the experience of aircraft reconnaissance. During the Cold War, satellite images were also provided by the US and the USSR to countries such as Egypt, Israel, Iraq, Libya, South Africa, South Korea or Taiwan, for security reasons.[40]

40. *Louis J. Levy and Susan B. Chodakewitz, "The Commercialisation of Satellite Imagery, Implication for Cross-Border Conflict"*, Space Policy, *August 1990, pp. 210-220.*

Appendix D

Composition of the IAEA's Board of Governors

Article 6 of the IAEA's statute institutes a Board of Governors. This body has 35 representatives, usually designated and elected at the Board of Governors' June session. Thirteen countries are designated once a year and 22 countries are elected every two years. They are chosen from the eight geographical zones in which the world is divided.[41]

1994–95 Board of governors:[42]

Geographical Zones	Elected countries 1993	Elected countries 1994	Designated countries
North America			Canada † USA †
Latin America	Colombia Cuba	Brazil † Mexico † Uruguay	Brazil †
Western Europe	Ireland † Switzerland †	Spain † Turkey †	France † Germany † Italy † UK †
Eastern Europe	Poland Ukraine †	Slovak Republik	Russia †
Africa	Ethiopia	Algeria Ghana Morocco	Egypt †
Middle-East & South Asia	Lebanon Tunisia	Pakistan †	India †
South-East Asia & Pacific	Indonesia † Philippines †	Thailand	Australia † China †
Far East			Japan †

† Known space data interpretation skills (see Appendix C)

The 1994–95 list has been released at the end of September, after its approval by the general assembly. India has been elected chairman of the board for this year.[43]

41. *Telephone interview with Hans Friedrich-Meyer, IAEA's Public Information Division, 17 August 1994.*
42. IAEA Press Release *94/35, 22 September 1994.*
43. *"India elected chairman of the IAEA board"*, Times of India, *27 September 1994.*

Appendix E

Technical Study: Monitoring of Potential Nuclear Testing Areas Using Remote Sensing Satellites

Update of Chapter III (3) in the 1990 VERTIC study: "Scientific and Technical Aspects of a Comprehensive Test Ban Treaty"

This appendix explores the technical requirements for utilising remote sensing satellites, both civilian spacecraft and "national technical means satellites", to obtain information about activities being conducted at known and suspected (potentially new or clandestine) nuclear weapons test sites as part of the regime for monitoring a Comprehensive Test Ban Treaty.

Number of Sites

Existing test ranges

Nuclear weapons are presently tested only by the People's Republic of China among the existing nuclear weapons states which include the United States, Russia, the United Kingdom and France. The United States test site in Nevada remains at the ready, should President Clinton order a resumption of American testing in response to tests carried out by other nations. Mr Clinton recently extended the American testing moratorium until at least September 1995, barring unforseen tests by other parties, and the United States elected not to resume testing after the October 1993 Chinese detonation. Because the Nevada Test Site is being maintained so as to permit resumption of tests shortly after a Presidential directive to fire a device, it is likely that reactivation of the range would not require extensive and highly visible conventional construction. The same is probably true for the French and Russian test areas.

One nuclear test was conducted by India in May 1974, thus establishing it as a country which must be similarly monitored.

The United States

Within the United States, tests have been carried out in Alaska, Colorado, Nevada, New Mexico and Mississippi. Until the ratification of the Limited Test Ban Treaty in 1963, the United States also conducted tests at its South Pacific test range including Eniwietok and Bikini atolls. The experiments conducted in Colorado and Mississippi were part of the defunct "Plowshare" programme to explore the use of nuclear explosives for peaceful purposes. It is highly improbable that either area could ever be used again for nuclear testing because of the likely public opposition. Those sites can be excluded from consideration. The Alaskan experiment was also probably a "one off" test, not to be repeated. Use of the site is no longer feasible because of environmental concerns. Civilisation has encroached on the site of the Trinity test north of Alamogordo, New Mexico; it is also not likely to be used again. The Pacific Test Range has only been used for air, space, and underwater based tests and is closed.

The United States thus maintains one active nuclear test range located near Mercury, Nevada, north and west of the city of Las Vegas.

Russia

Russia maintains two nuclear test sites at the Novaya Zemlya test range in the Arctic. The former Soviet Union also maintained two additional sites in what is today the independent state of Kazakhstan: on the Shagan River, and at Degelen Mountain. The latter two ranges are often referred to collectively as the Semipalatinsk test area. Novaya Zemlya has not been an active range in recent years, but the (former) USSR announced early in 1990 that over a period of three years the Soviet testing programme would move, in total, from Semipalatinsk to Novaya Zemlya.[44] The last Soviet test, in October 1990, was conducted at Novaya Zemlya.

The United Kingdom

The UK formerly tested nuclear weapons in Australia and in the South Pacific. It now conducts all of its tests at the American Nevada Test Site. There is no reasonable probability that the UK will be able to resume testing in Australia; if the United State continues its moratorium, no further UK tests are likely to occur.

France

France tests at its Pacific Test Range based on the islands of Moruroa and Fangataufa These coral atolls are located within the Tuamotu Islands group. The French site i unique in the world in that the explosions are conducted in tunnels which ar themselves run beneath the ocean floor. Emplacement is through drill rigs located o the island itself and capable of drilling on a slant. It is unlikely that France would eve again be permitted to test at its former Sahara Test Range in Algeria.

China

China operates one acknowledged range near Lop Nor, in the Xinjiang Autonomou Region.

India

India, having conducted only one full-scale explosion in May 1974 in the Rajastha Desert, can be presumed to have only developed this one area as a nuclear test sit Because of the size of the country, it cannot be ruled out that other areas could b developed as well.

South Africa

The Republic of South Africa (RSA) is the only nuclear power which has voluntari decommissioned its entire stockpile of special weapons.[45] The RSA constructed o acknowledged nuclear test site with two rather shallow bore-holes for nuclear devices the 1970s. As part of the 1992–93 termination of the RSA nuclear weapo programme, both bore-holes were filled in such a manner as to make using the site mo difficult to re-establish than constructing a new one. While South Africa is unlikely resume a nuclear weapons programme, the Kalahari Desert site could be monitored, a confidence-building measure.

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44. *For a good satellite survey of Novaya Zemlya, see Johnny Skorve,* The Kola Satellite Image At Perspectives on Arms Control and Environmental Protection, *the Norwegian Atlantic Committee, 1991.*

45. *Videotape of test supplied by officials of the South African Embassy, Washington.*

Potential test ranges

North Korea

As the nation currently of greatest proliferation concern, the Democratic People's Republic of Korea (DPRK) may be contemplating the establishment of a nuclear weapons test range, particularly if it has plans to construct a stockpile incorporating one or more of the advanced weapons design techniques which do, in fact, require testing or data from experienced weapons designers. North Korea is, therefore, a nation which must be on the list to be monitored.

Israel

Israel has a nuclear arsenal of up to a hundred bombs. It is assumed that these were manufactured without nuclear testing. Although site and population distribution would be a problem, a clandestine site in Israel's Negev Desert is not an impossibility.

Other States

All nuclear threshold countries with the exception of Taiwan have sufficient sparsely settled areas to permit them to establish one or more nuclear test sites. The states counted as being on the nuclear threshold include Libya, Iran, Iraq, Israel, Pakistan, Taiwan, North Korea and South Korea. Consideration of this list adds ten nations with the possibility of having indigenous test sites (Taiwan is excluded on grounds of territorial size). Brazil constructed a test site which was subsequently "destroyed" by filling in the borehole

Total number of test ranges to be monitored

Around seven active or readily re-opened nuclear test ranges can be counted throughout the world. To that number must be added at least one range within each nuclear threshold country. Should the NPT regime fail, additional nations which have the technological base for nuclear weaponry would have to be included.

The number of sites which must be monitored is, therefore, on the order of 20, but could be as much as a factor of two larger, should some nations utilise more than one site or should the non-proliferation regime collapse.

It is important to recognise that no nation entering the nuclear club is likely to require a full-scale test with significant nuclear yield of any weapon resembling those in the first generation of the American stockpile (i.e. gun-assembled fission weapons using ^{235}U as the fissile fuel or simple implosion-assembled weapons using either high-enriched uranium or ^{239}Pu with relatively small amounts of ^{240}Pu as a contaminant). South African officials have clearly stated that they did not need and did not desire a test of one of their six HEU-fuelled devices – although their nuclear doctrine called for a test at some point if it became necessary to establish a deterrent capability beyond any doubt.[46] Iraqi scientists also indicated to IAEA inspectors that they felt no need to test their uranium implosion weapon, except with non-fissile materials to verify the correct functioning of the high explosive assembly.

46. Stumpf, op. cit.

Utilisation of Monitoring Satellites

This technical appendix concentrates on the monitoring of *underground* nuclear tests on the grounds that even the most likely proliferants (North Korea excepted) are Parties tc the Limited Test Ban Treaty of 1963 and are unlikely to conduct atmospheric nucleaı tests. Specialised satellites such as the earlier VELA/HOTEL series operated by the United States are necessary to detect and identify atmospheric tests with tolerable lack of ambiguity. Preparations for an atmospheric test are similar to those for an underground test except that no bore-hole need be drilled, and no tower erected. Instead, an above *land* test can be conducted using a balloon to hold the device; and aı ocean-based test can be carried out from a barge or a balloon. The site of aı atmospheric test on land is, however, likely to be distinctive as a tour of the Nevad: Test Site will show.

A naval task force to conduct a test at sea is also likely to be distinctive, but will no present a target for monitoring by imaging satellite except for a time on the order o hours or days. It is possible that broad ocean area searches using synthetic apertur radar might provide warning of the assembly of such a task force; this is particularl true if the radar were cued by communications intercepts. Unfortunately, the need fo radio silence when conducting questionable activities is well known; COMINT may nc be of much assistance.[47]

General considerations

The frequency with which any site can be observed depends on several factors. Th most important of these is the repeat period of the satellite orbit, the time it takes befoı the ground track of the satellite "exactly" retraces a previous track. For Spot this peric is 26 days. Of nearly equal importance is the distance the satellite can look to either sic of its ground track. Spot uses mirrors on its two cameras, permitting the viewing axis t be tilted up to 27° to either side of the nadir point. Thus, Spot is able to observe targ points located up to about 425 km to either side of its ground track; the resolution slightly degraded at large off-nadir angles. In practice, this provides a revisit interval not more than five days at the equator and considerably less in temperate latitudes.

The ability to peer across track is an important one for a monitoring satellite, for greatly increases the area on the ground "at risk" of being observed on any one track. the repeat cycle of a satellite is only 14 days, the period of the Russian "Resourc satellites carrying KFA-1000 cameras, and if the camera is constrained to point at – nearly at – the nadir point (as do the instruments on both the Landsat and "Resourc satellites) then workers on the ground can be confident of having two weeks or mc between chances of being detected while engaging in clandestine activities. It therefore, almost a necessity to have the ability to point the cameras on the satellite. concomitant necessity is the ability to keep secret the programme for acquisition imagery so that potential evaders must engage in camouflage and concealment activit whenever the observation satellite passes within visual range. The inclusion of a nc interference clause in the treaty would therefore be an important measure for confideı building. Detection of activity which did appear to be camouflaged could, by its trigger suspicion. A greater off-nadir capability than that possessed by Spot would useful in a test ban monitoring situation.

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47. *See forthcoming* Test Ban Verification Matters *issue on hydroacoustic detection.*

Maximum frequency of acquisition

The maximum frequency with which a single Spot satellite can observe a given site at the equator is once in five days, or 73 times per year. If Spot were supplemented by Radarsat (a Canadian project with a 10 metre resolution), that frequency could be roughly doubled. It will be seen that observing a single site 140 times a year generates an overwhelming stream of data, given that interpretation of a single Spot scene requires 40 to 80 working hours.[48] That is sufficient time to enable trained and experienced analysts to scan a new picture, satisfy themselves that they have identified all sites which meet their search criteria and to make quantitative measurements and draw qualitative conclusions about identified sites. One can not of course guarantee that all sites of significance have been discovered, particularly in the presence of deliberate concealment measures. Furthermore, it is unreasonable to expect Spot or any other satellite operator to make its instruments available on such a regular basis, particularly since there are apt to be other targets of (commercial) interest which cannot be accessed if the camera is trained on the monitored areas on every possible pass.

Nations operate reconnaissance satellites for the purposes, *inter alia*, of acquiring intelligence and monitoring compliance with arms control accords. However, this appendix considers primarily the acquisition and analysis of images from open sources. Open images can be widely distributed for analysis, and can – to first approximation – be handled without taking those precautions appropriate to material collected by intelligence sources and analysed with methods used by the intelligence community.

A monitoring authority relying upon commercial image vendors such as Spot-Image or Radarsat International might be able to command one image of each site during each repeat cycle. For Spot this corresponds to 14 images per year of each site, although some images, at least, will be lost due to cloud cover. In order to complicate any possible efforts to carry out preparations for a test without detection, some of these Spot images should be supplemented, or even replaced, by images acquired from other platforms.

Fortunately, the weather requirements for nuclear test sites generally make their observation from space easier than observation of a random point on the earth. That is, test site preparation normally requires significant construction out of doors, drilling, laying of cables, etc., which has, historically, led to test ranges being located in areas with good weather and low precipitation. In addition, requirements for physical security of the site and for control of fallout from either an atmospheric test or an underground test which is poorly contained, dictate that the test range be isolated from populated areas. Arid locations are generally the most sparsely populated and easiest to keep secure.

One rule of thumb is that temperate areas have 50% or more cloud cover about half of the time; desert areas are obscured far less of the time. Images with 50% cloud cover are unlikely to have much utility for monitoring; a 20% maximum is probably the practical working limit – although, of course, luck has a role to play in whether the cloud cover is 90% or 1%; a single cloud in a picture covering a large region can obscure the precise target site. Novaya Zemlya is a specific exception to the notion that

48. Interview with Donald Vance, then head of military photo analysis for the Washington-based firm of Greenhorne & O'Mara. The same judgement is made by William Kennedy of the Eros Data Center.

nuclear test sites usually have good weather. It is only possible to get imagery of Novaya Zemlya a few times a year.

Because of cloud cover, close to 25% of acquired scenes, even in desert areas, are apt to prove less than fully useful – based on an inspection of the Landsat 4 and 5 catalogue of imagery over the Nevada Test Site with a 20% cover taken as the maximum permitted. Statistically, then, of 14 scenes acquired per year, only ten will be useful.[49] While the distribution of those scenes is statistical, it is not wholly random since weather patterns are predictable, and certain periods of the year are far more apt to have obscured skies than others. However, potential violators would be equally aware of weather patterns, both annually recurring ones and short-term developments. They can, if the monitoring agency relies upon optical reconnaissance, use their knowledge of local weather to reduce their chances of being detected before a test is carried out.

Understanding of the utility of cloud cover for concealment requires:

- an estimate of the amount of time required to prepare a test site;
- information concerning the amount of time over which seismic arrays can remain tuned to optimise signal detection from a single area; and
- information indicating the likely timing of a nuclear explosion, and calculation to ensure that arrays can be aimed within that period.

Further discussions of the utility of satellite observations to provide warning of a clandestine nuclear test are predicated on the assumption that the test is to be carried out in such a manner that the conventional construction and emplacement of data transmission cables, etc., are carried out so that they are, in fact, visible from above. This need not be the case, particularly if the test is to be conducted in an area in which no nuclear testing has occurred previously and in which suitable underground facilities already exist (e.g. in an existing deep mine).

The rate at which observation of any given suspect area must be attempted depends on several parameters:

- The length of time required for site preparation before a test occurs, including drilling of the emplacement hole and any instrumentation holes and tunnels, as well as the period needed to build on-site data collection facilities, to emplace the device and to stem all the holes. (T_1)
- The time after construction begins until the purpose of the activity is unambiguous, or at least highly indicative. (T_2)
- The confidence, (C), with which probable cause must be established before issuing an alert to the seismic system or to an international on-site inspection agency.
- The weather pattern (at the given season) over the suspect test site, or, alternatively, the availability of weather-independent satellites such as Radarsat. Assume the cloud-free fraction at the local time of satellite passage to be given by (f). Alternatively, one may consider (1-f) to be the probability that real test-related

49. This fraction is approximately correct for the Nevada Test Site; Lop Nor and Semipalatinsk are worse; the French test range in Algeria was probably somewhat more favourably located from the point of view of satellite monitoring.

activity would be detected in any one attempt to image the site if the activity actually exists.

- The period needed to analyse the imagery and to conclude that probable cause to beamsteer the seismic arrays exists, as well as the additional time needed to steer the beams of the seismic system. It should be noted that in practice the time to obtain political authority to steer the beams is likely to exceed greatly the amount of time needed to implement the steering using the computer system which controls the phasing of the seismic arrays. Because of the political sensitivity of such an action, it is unlikely to occur without consultation at the ministerial or subministerial level.
- The gain in monitoring confidence obtained by steering the seismic arrays.

Only some of the above points can be readily quantified. At least one successful observation is needed in each interval of time T_0 where:

$$T_0 = T_1 - T_2. \tag{1}$$

One may guess that T_1 is on the order of three months, and that T_2 is on the order of two weeks to one month. Thus, one must obtain one useful image of each potential test site every second month.

This is a simple statistical problem:

$$(1 - C) = (1 - f)^n, \tag{2}$$

so that n, the desired number of observations, is given by:

$$n = \log(1 - C)/\log(1 - f). \tag{3}$$

For the nominal case of 95% confidence and 25% probability of failure to acquire an image in a given attempt (i.e. 25% of the time the site will be obscured by cloud or that technical difficulties will prevent a satisfactory image from being acquired), 2.41 attempts are required. Since acquisitions only come in integer numbers, either two or three tries must be made. With two attempts, C, the confidence level, is 93.75%; if a third attempt is made, C increases to 98.4%.

This example cannot quantify, except by folding into f, the possibility that a successful acquisition is made, but that the observation is thwarted by camouflage, concealment and deception (CC&D) on the part of the observed state. Given that the observed state is assumed to be engaging in prohibited behaviour, the probability is very high that CC&D measures will be attempted. It will be important for the monitoring system to be able to detect the presence of CC&D with high confidence, *even when it cannot strip away the camouflage to reveal what has been deliberately obscured.* The detection of a camouflaged area in a region capable of being used as a nuclear test range in a nation reasonably suspected of wanting to test a nuclear explosive should itself be cause for concern, perhaps sufficient cause to warrant requesting a special inspection and beamsteering.

T_0 is on the order of two months; the desired number of acquisitions within that period is roughly 2.4, leading to a desired acquisition rate of a = 1.2 pictures per month, or about one attempt every fourth opportunity. Note that these acquisitions cannot occur on a regular and predictable schedule; if they do, CC&D is made far simpler. Thus, acquisition opportunities must be scheduled randomly, and the schedule must be held secret from the nation to be observed. Spot-Image, however, offers a "Red Service" (called "Special Service" in North America) which permits a client to purchase the entire capability of the satellite over a significant arc of its orbit. One effective CC&D measure would simply be to purchase Red Service for the arcs from which the clandestine test site was in view for a sufficient time period before (and after) the planned detonation. Unless the monitoring authority has such quasi-governmental stature that Spot-Image cannot reject its scheduling requests, Spot may be of very little utility since the cost of Red Service and purchase of all acquired images over a three month period is minuscule compared with the cost of a nuclear test.

Commercial satellite operations and operators are, by definition, motivated by the desire to maximise return on their investment in satellites and ground installations. Profit-driven remote sensing systems, therefore, cannot always be counted upon to provide acceptable coverage unless government or UN intercession should prove successful. However, the monitoring authority might consider whether the booking of Red Service of a test site were not, itself, sufficient indication of a need for increased seismic monitoring. In the grey world of intelligence measure and countermeasure, there is no clear answer. Red Service could be booked over an innocent area in order to divert attention from clandestine test preparations occurring elsewhere.

Multispectral sensing for detection of clandestine test sites

It must be assumed that any nation which is party to a comprehensive test ban agreement but which, nevertheless, elects to conduct a nuclear test will do so in utmost secrecy. It is probable that such a nation will take pains to see that its preparations for testing are not readily observable from reconnaissance satellites, or if they can be seen, lack such characteristics as would positively identify them. Thus, it is improbable that even high resolution satellites would be presented with the kind of obvious preparations which are seen in images of the 1989 Joint Verification Experiment in which US and Soviet scientists conducted joint nuclear tests at the tests sites of each country to study means to determine the yields of nuclear explosions.[50]

Such clandestine testing could be conducted in a large, deep, and active mine comparable in size to, say, the Kirunavaara iron mine in Kiruna, Sweden. In a mining operation of such scale the additional earth-moving machinery necessary to excavate horizontal tunnels – or even to bore vertical shafts starting from an existing tunnel – would go unnoticed. The construction spoil from a tunnel, perhaps the most visible signature of such an operation, could even be hidden in played-out regions of the mine. Until the arrival of the nuclear device itself not even an increased level of security need be maintained, although some attempts to conceal the purpose of the special construction from miners employed for the normal work of the facility would have to be made.

Under these circumstances – or under similar scenarios for other parts of the world – it is unlikely that any obvious indications would appear before the test which could either

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50. M. Krepon, P.D. Zimmerman, L.S. Spector, and M. Umberger, editors, Commercial Observation Satellites and International Security: *William Leith and David Simpson, 'Monitoring Underground Nuclear Tests", St. Martin's Press, New York and Macmillan, London, 1990. The Leith-Simpson article shows Spot imagery of the Semipalatinsk test range in Kazakhstan.*

alert the seismic network or which could be used to pinpoint the site of the borehole or tunnel. Hence, detection and identification of the nuclear test would have to wait until the test took place. While seismic means alone should provide strong evidence that an explosion had occurred, teleseismic arrays cannot be expected to locate the epicentre of the test more accurately than within a few kilometres. Given the clandestine nature of the test, the testing country may choose to test out of range of a local seismic array, if possible.

Pin-pointing the epicentre with enough accuracy to permit an on-site inspection team to conduct an efficient inspection – an area roughly in the order of one kilometre in diameter would be good enough – must therefore, be done by observing construction work to emplace and test a device or by examining the site *post facto* to find surface changes produced by a large explosion at a depth so great that the rock overburden prevents venting and – more importantly – the formation of a collapsed crater.[51]

Recent research examining the Nevada Test Site and Semipalatinsk shows clearly that activities uniquely related to nuclear testing *as conducted at those two sites* is easy to detect and identify either before or after an explosion. At the Nevada site, signatures of underground tests include alterations of the thermal properties of the ground, slight "expansion" or distortion of the precise geography in the spall zone so that "before" and "after" images of the same area do not exactly register, and the spalling of dust to cover nearby vegetation and reduce the near-infrared reflectance. The latter effect only lasts until the first rain or the first high wind after the event. At Degelen Mountain in Kazakhstan the hard weathered granite of the surface is spalled off leaving a bright area of unweathered rock marking the ground zero.

Early work on the Lop Nor test range indicates a different kind of situation.[52] While test locations can be identified on Landsat imagery, the extremely distinctive construction seen at NTS and Semipalatinsk is largely absent. One does not see large cleared rectangles with circumscribed circles (the fence line), cables laid over the bulldozed areas leading to instrument trailers set next to one another at one end of the area. The Chinese activities, pre-test, are less distinctive and less easy to detect in a single image than are either American or Soviet construction practices.[53]

Effective on-site inspection requires knowledge of the location of the shot and the associated bore-hole or tunnel complex to no worse than one square kilometre; otherwise, the area to be searched on the surface is too large, and the likelihood of being able to sink an inspection shaft into the cavity produced by the test is very low. According to Los Alamos testing specialists, present-day seismic networks can localise an underground blast in an area not previously studied to an ellipse roughly 50 km x 70 km, which is manifestly insufficient.

Thus, surface indicators which can be used to identify and localise deep underground explosions must be found. Fortunately several such signatures exist; some have been

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51. Clearly, if a collapsed crater is formed by an underground test, this new feature will be quite readily detected on Landsat or Spot imagery. Such craters are typically one to three hundred metres in diameter, depending upon the yield of the device, the depth of burial, and the local geology of the site of the detonation.

52. Vipin Gupta, Ph.D. Dissertation, Imperial College, London, 1994, unpublished.

53. For Spot images of tests in tunnels under Degelen Mountain and of the vertical "Joint Verification Experiment" see Leith and Simpson, op. cit.

used already to locate underground tests, while others are in development.[54] All techniques require multispectral information, and the more sensitive ones under development require data from Landsat bands 5, 6, and 7 as well as bands 3 and 4 because they are used to detect alterations in the morphology of surface soils caused by the passage of the shock wave produced by the explosion from the ground (where the speed of sound is high) to the air (where it is much lower).

A significant advantage to such imaging techniques is that the area surrounding the epicentre appears as an approximate circle at most a few hundred metres in diameter. The centre of this circle can be located with high precision, thus giving an accurate location of the epicentre of the test. Several test areas in the Nevada Test Site have been imaged and analysis indicates that the thermal diffusivity of the ground appears to rise within the spall zone,[55] roughly as large in diameter as the depth of burial of the device under US testing practices. This rise in diffusivity means that a thermal image acquired in the morning will show the spall zone somewhat cooler than surrounding similar terrain because the shocked region conducts the solar heat away more rapidly than does the unshocked area.[56]

For the foreseeable future it would be unwise to rely on monitoring techniques which use the Landsat thermal sensor. The Thematic Mapper instrument on Landsat 4 is no longer functioning, Landsat 5 is clearly approaching the end of its life, and Landsat 6 was lost at launch in the Autumn 1993.

Cost of Acquisition and Monitoring

The costs of acquisition and data analysis scale linearly with the number of images obtained – the scale factor being the price of each image as set by the supplier plus the cost of data analysis per acquired image, unless a quantity discount is given for acquiring imagery. Both the acquisition and analysis costs will vary depending upon the satellite used. Radarsat International might charge less for its imagery than Spot-Image, but SAR imagery requires significantly more computer processing to be useful. Landsat 4 and 5 provided 30 metres resolution in 6 spectral bands at far lower a cost per square kilometre than does Spot – but the increased spatial resolution from the French instrument may be crucial.

The cost of an image acquired to order by Spot is presently approximately US$ 3,300. Between 40 and 80 working hours are required to analyse each Spot image – more being required while the sites of interest within the scene are being located, and fewer

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54. Leith and Simpson, op. cit., and B. Jasani and C. Larsson, "Security implications of Remote Sensing," Space Policy, *February 1988, p. 56, for the use of two somewhat different techniques, one exploiting Spot's near IR band to detect reduced IR reflectances caused by spallation dust covering low-lying vegetation at Semipalatinsk, and the other using Landsat Band 4 to seek increased vigour in the vegetation surrounding collapse craters in Nevada (presumably caused by cracking of the surface which improves the collection of water). Jasani and Larsson misidentify several large circular formations - on the order of 2.3 km in diameter - as surface signs of subsurface testing. In fact, they have observed changes in the desert ecology caused by the thermal radiation from above ground tests conducted no more recently than 1958.*

55. The spallation zone is that area over which the surface is accelerated vertically to at least one times the downward acceleration of gravity. Within the spallation zone rock, soil, vegetation, and human-made items on the surface are thrown violently into the air and "slap" down afterwards. The spall zone is marked by relatively large cracks in the surface, but otherwise is difficult to detect with the un-aided eye.

56. Peter D. Zimmerman, Final Report of Research Performed Under a Subcontract from LLNL, Center for Strategic and International Studies, 1993.

once the analyst has achieved a high degree of familiarity with the scene and is able to use computer-aided change detection methods. For simplicity, 60 working hours per scene will be assumed needed for each scene acquired (not for each test area monitored).

The Nevada Test Site (NTS), which appears on US maps, so its area can be readily estimated, occupies a roughly parallelogram shaped area 120 km by 150 km. If imagery could be oriented as one might wish this would require a minimum of five scenes for complete coverage.

The actual shape of the area, however, is such that at least seven scenes would be required for complete coverage. The central area of the test site, which contains both Yucca Flats and Frenchman's Flats – two of the most used test areas – as well as the headquarters area at Mercury, Nevada, is much smaller, requiring only three scenes for coverage. (These scenes cannot be acquired on a single orbit of the satellite; indeed, they might have to be acquired over the space of a week).

To monitor NTS, **3 x 12 x a** (where a is the number of images which must be acquired each month as determined by considerations outlined above and 12 is the number of months in one year) scenes must be acquired each year. For the previously estimated rate, that means that 43 images a year must be purchased and analysed. The cost to acquire the imagery of NTS is thus

US$ 3,300 x 43 = **US$ 141,900** per year

The analysis of 43 scenes requires 2580 working-hours (at 60 working-hours per scene). Assuming 4 weeks of paid vacation, 3 weeks of sick leave, and 10 days of paid holiday time (reasonable professional benefits in the United States), there are 43 working weeks per year, or 43 x 40 = 1720 working hours in one working-year. Monitoring NTS thus requires 1.5 working-years of photo-interpreter time. The salary of an American photo-interpreter capable of exploiting computer analysis techniques is (1994) roughly US$ 42,000 (plus benefits such as medical and retirement insurance, which typically add 28% to personnel costs at universities and similar employers).

The personnel costs to monitor NTS alone are thus:

US$ 42,000 x (1.28) x 1.5 = **US$ 80,640** per year

exclusive of any indirect costs, costs of administration, office supplies and support.

We have seen that the number of potential sites to be monitored, world wide, is on the close order of twenty. If the sensitive area of NTS is comparable in size to that of each of the other 19 areas to be monitored, then the cost of monitoring is:

Personnel: US$ 81,000 x 20 = **US$ 1,620,000** per year

Imagery: US$ 141,900 x 20 = **US$ 2,838,000** per year

Total = **US$ 4,458,000** per year

plus administrative, equipment, maintenance and other costs including office space. Thirty photo analysts will be needed for the project, assuming that no additional areas of concern are developed. Additional imagery may have to be acquired to establish the historical record of activity at each monitored test site, but this will be a one-time expense. One support person for every four analysts is probably a minimum – including technical, maintenance, book-keeping, clerical, etc. – although those personnel categories are generally lower paid. In addition a library and library staff will be needed to obtain, store, and retrieve the kind of collateral information which is absolutely required for good intelligence. No fewer than four or five high-level political analysts will also be required, as well as a senior administrator and his/her deputy if the monitoring organization is to be included within the structure of an existing body. If the monitoring organization is to be free-standing, the number of support personnel might well double and the number of senior managers will certainly increase from two to four or more.

The base costs for operating a monitoring agency – imagery and analysis staff – are remarkably affordable so long as the area to be studied is relatively small and can be defined in advance. Nevertheless, one should *not* take the costs estimated here to be the correct costs or the actual costs of a satellite monitoring operation for verification of a comprehensive test ban. The costs estimated in this report are quite specific to the assumptions made about the areas to be monitored, the confidence levels needed or desired, and the likely numbers of "missed" imaging opportunities due to cloud cover and the like. A further assumption is that it is unnecessary to resort to excessive numbers of pictures or sophisticated monitoring satellites in order to penetrate concerted deception schemes. It is worth noting that the total area monitored in this case study is less than a quarter million square kilometres – about the size of Oman, a bit smaller than New Zealand, roughly the area of Laos but only one tenth that of Indonesia, approximately one third that of Texas, half the area of Sweden but about the same as Romania, and almost exactly the size of Guyana.[57] Under other assumptions the costs to monitor potential test areas could increase greatly.

Capital Equipment

Method of estimating required equipment

Image analysts work best in teams of two, one providing a "sanity check" on the other, and both working to bring to bear complementary types of experience. Thus, the staff of thirty photo-interpreters will be organized into fifteen teams of two, probably organized into three squads of five teams each, each squad with a designated leader.

It is possible to work two shifts per day in a military environment, but probably not in a civilian one. In 1990, the VERTIC Report suggested that one work station for each team would be ideal, "but probably not necessary since much of imagery analysis takes place off-line". That is, much of the time of the analyst is spent in library research, in comparing imagery of the same site taken on different dates, in seeking and examining imagery of similar sites, and in writing reports. As we will see in the next section, the situation has changed.

Number of computer workstations and other peripherals

Under the assumptions made in 1990, 15 workstations would have been ideal, and careful scheduling would have allowed the agency to operate with only ten. Each computer work station (e.g. a SUN UNIX-based workstation) costs, including software,

57. The actual area to be monitored is computed to be 216,000 square kilometres under the assumptions of this study.

roughly US$ 30,000 – US$ 50,000, depending upon the capabilities demanded. But very powerful lower-powered work-stations are now available based on Pentium series desk-top computers, and even "486"-based machines can be perfectly satisfactory. A careful study must be made to determine the trade-offs between capability and cost. In general, as time goes on, capability will increase and cost decrease. Given the need in today's world to provide every analyst with a computer at least as powerful as a "486" for ordinary office tasks, physics analysis, and modelling, and the small additional expense of putting image-processing software and a high-quality monitor on each such machine, it is now appropriate for *every* analyst to have his or her own image processing system.

This is a situation which could barely have been anticipated when the first version of this study was prepared in 1990! For example, in 1991, a 540 Mbyte hard drive (essential mass storage for large images) was an exotic and expensive device; in 1994, they can be purchased for home machines for less than US$ 400.

In addition to the computer work-stations, a shared "hard copy" device capable of providing photographic prints both for off-line analysis and for distribution is required. In 1989 a 3M printer capable of doing the job cost about US$ 250,000; in 1994 it should be possible to purchase any of several thermal-transfer printers for less than $25,000. In addition, it is possible in 1994 to write the images to "TIFF" files and send those files to commercial services which will prepare colour slides or negatives at costs of a few dollars per image or less in quantity. Imagery can also be distributed today on Kodak-format "Photo CDs".

First year capital cost

The start-up price for the monitoring agency's computer work-stations and output devices is, therefore, between US$ 375,000 and US$ 550,000. Other capital costs for word processors, furniture, and office equipment must be added to this budget. It would not be unreasonable to budget US$ 5,000 per employee for this category.[58]

Maintenance

Annual maintenance costs, equal to 10% of the price of the equipment, should be considered a minimum. In addition, the annual cost of upgrading equipment to meet evolving standards of performance must not be ignored. This can range between 10% and 25% of the initial capital cost, based upon personal experience with computers ranging from IBM PCs to VAXs. At least two people for maintenance of the workstations were included in the personnel estimates made above; using outside contractors would not appear to be appropriate: first because of the need to have maintenance personnel available 24 hours a day, and second because of the probable need for security clearance at a very high level for all those connected with the agency.[59]

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58. Compare with the 1989 start-up costs of US$ 775,000 - US$ 1,250,000. The cost of computer equipment has continued to decline. This decline is what has made the equipping of every analyst with an image processor seem feasible today (early 1994). Unfortunately, the cost of imagery has increased significantly in the same period.

59. While most studies of nuclear test sites using civil remote sensing satellites have been done on an unclassified basis or at a low level of classification, one must carefully consider the difference between research and the specific monitoring of sovereign nations by an international body for the purpose of assessing compliance with a treaty or of identifying violations of the accord. The research can be done openly; the diplomatic, military, and intelligence components of the verification and monitoring process require a

After a monitoring agency is established, the operation of a centre for the analysis of remotely sensed imagery should not cost in excess of $6,500,000 per year, including all personnel, imagery, and maintenance but not including lease or rental of office and laboratory space nor the overhead associated with maintaining secure facilities and ensuring the trustworthiness of the employees.

Construction and operation of dedicated satellites

It is plausible for a well-funded monitoring agency to consider the construction of dedicated satellites for its specific purpose. The cost of such satellites need not exceed $150–$200 million per satellite for construction and launch if care is taken in the design process to avoid the inevitable temptation to push technology and produce a wholly new satellite. If a cost-effective product is to be obtained, it can only be produced by adapting an existing design to the needs of the system.[60]

Given the fact that any violations of a CTBT agreement would be conducted in secrecy and with care given to present observation from above, it may well be that no observation satellites will be useful for detecting preparations for a clandestine site. Increasing the number of satellite would increase the probability of detecting preparations.

Satellite characteristics

Extremely high spatial resolution is probably not required to detect the construction needed to operate an open test site. Both Spot and Landsat images have been used to observe activities at nuclear test sites – Landsat of the Nevada Test Site and Spot of Semipalatinsk,[61] Novaya Zemlya, and Lop Nor. At the ten metres resolution level trailers and other temporary laboratory structures will not be readily detectable or identifiable; at five metres, they should be.

This indicates that a modification of the Spot panchromatic sensor to the five metres level – requiring either an increase in the data transmission rate by a factor of four, a reduction in the word length describing each pixel by a factor of four, or a reduction in the covered area to a square 30 km on edge – would be adequate. A reduction in the word length is inappropriate; Spot already uses an efficient data compression algorithm, and any further reduction in the word length would require a reduction in the dynamic range or the detail which could be conveyed. It is important to recognise that the data transmission rate and the volume of data which can be stored on the on-board tape recorders do set the effective limits on the combination of resolution and coverage area. The data transmission rate of Spot 1 already pushes the state of the art for unclassified systems.

Given the impossibility of searching vast areas with Spot, Landsat or any other close-look instrument, simply doubling the focal length of the Spot telescopes to reach five

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high degree of confidentiality. The activities of the IAEA in Iraq and North Korea demonstrate how intelligence information is used, and how it (and other activities) is protected by an international body.

60. Pierre Bescond, then President of Spot-Image Corp., Reston, VA. Talk given at the Virginia Center for Innovative Technology, Herndon, VA, 18 January 1990. Bescond estimated that the marginal cost to build and launch a duplicate of Spot 1 would be between $150M and $200M in 1990 dollars.

61. Jasani and Larsson, op. cit., Skorve, op. cit., Gupta, op. cit. and Leith and Simpson, op. cit.

metres resolution and accepting the reduction in coverage area is probably the most cost-effective solution. As an added benefit, the XS resolution would also be improved, to ten metres. One possible compromise might be to adapt a Spot 1 satellite to have one telescope with doubled focal length and reduced coverage while the other retains its original resolution and larger coverage. Note that such a hybrid satellite would have lower revisit intervals at high resolution than would a satellite with two long focal length telescopes but it would have a higher overall revisit rate if the lower resolution instrument were included. However, the reduction in area coverage probably would decrease over-all revisit frequencies since the maximum off-nadir distance in either direction would be decreased by 30 km, half the size of the original scene.

It is also not clear if the spectral range and resolution of the Spot XS sensor are adequate for the detection of subtle surface changes produced by deep underground explosions fired in soft-rock geology. It may be that a sensor comparable in spectral range and resolution to the Thematic Mapper on Landsats 4 and 5 is required. A monitoring agency must be capable of localising the epicentre of any suspicious event to within roughly 100 m if on-site inspection is to permit direct confirmation of the test by actually drilling into the cavity. Since this cannot be done seismically, it must be done with imagery or on-site inspection techniques discussed later. Furthermore, the monitoring agency will have to be able to have some capability to detect and identify nuclear explosions which were conducted in deep secrecy and with due care given to the reduction of all possible surface and seismic signatures.

It would not be easy, however, to adapt the Landsat sensor to obtain higher resolution. Thus, the problem of constructing dedicated satellites escalates since both a Landsat and a Spot equivalent are probably needed. In all probability the needs of the agency can be met better by constructing and operating an upgraded Spot system while relying on other suppliers for extended range multi-spectral sensors. "Lightsat" or "Minisat" (small satellites) techniques are probably not useful in this case, because of the difficulty of constructing cheap and light long-wavelength IR sensors.

Number of satellites for adequate coverage

This section uses the orbital parametres and technical specifications of the Spot 1 and Spot 2 satellites as illustrative paradigms. Each Spot satellite is in a sun synchronous orbit at an altitude of 832 km. And each satellite has the capability of pointing each of its two HRV cameras up to 27°– off-nadir. While each HRV can only image a swath 60 km wide at any given instant, the satellite is capable of imaging two simultaneous swaths located anywhere from nadir to 424 km off-nadir (centre point of outermost swath). Thus, on any one orbit a Spot satellite can collect data over a swath 848 km wide. In order to have even the possibility of once a day coverage of every point on earth at the same local solar time, several satellites must be placed in the same orbital plane, with average spacing along the orbital track so that the earth rotates 848 km (at the equator) between the time one satellite departs the equator and the next arrives.

Since the circumference of the earth is 40,000 km and the day is 24 hours long, the spacing interval between satellites is 30.5 minutes. The period of revolution for satellites at 832 km altitude is 102 minutes, which indicates that three satellites are required. Two satellites spaced 180° in true anomaly can provide coverage two out of every three days, even at the equator.

The above calculations assume that the verification satellites are in "sun synchronous",[62] near polar, orbits. This need not be the case. So long as the highest latitude potential test area is covered adequately, the inclination can be reduced and sun synchronous operation eliminated. The advantage to shallower inclinations is (if the satellite can scan off-nadir, cross-track) that successive ground tracks can be somewhat closer to one another at lower latitudes so that the temperate zone is covered more frequently than by a satellite in polar orbit. The disadvantage is that shadows change significantly from one observation opportunity to the next, complicating the use of automatic change detection programmes and the detailed pixel-by-pixel comparison of "before" and "after" images. On balance, the advantages of sun synchronicity probably outweigh the somewhat higher revisit rates provided by shallower inclinations.

In view of the long lead time to prepare a nuclear test site, it is not clear that daily or two-out-of-three day coverage is required.

Other considerations

In examining the costs and benefits to a monitoring agency for operating its own dedicated satellites, it becomes clear that the total area to be examined by the agency is very small compared with the area of the land masses of the earth. Furthermore, a monitoring agency with treaty-specific responsibilities does not have the needs of a national intelligence agency to collect information on all possible threats, world wide. It is therefore apparent that a monitoring agency cannot make efficient use of a satellite system for its own account. One solution would be for the agency to own and operate the system but acquire imagery for commercial clients and distributing it at reasonable cost under an "open skies, open access" policy. If the resolution, re-visit rate, and other specifications of the system made it attractive to prospective customers and gave it some technical advantages over the Spot, Landsat and other systems of the near future, such sales could be a quite attractive way to subsidise the monitoring activity. Alternatively, and probably, any CTB monitoring agency might find it more efficient to rely upon imagery provided by national intelligence agencies supplemented by appropriate pictures obtained from commercial, quasi-commercial or quango enterprises.

The high barriers to using intelligence imagery which appeared to exist when the previous version of this paper was written in 1989–90 have diminished if not disappeared. The Soviet Union has dissolved, and the successor states already have indicated a willingness to sell imagery with approximately a one metre IFOV as a source of hard currency. Furthermore, the Clinton Administration is a greater friend of a CTB than either the Reagan or Bush Administrations – which were both actively opposed to any limits on testing other than the Threshold and Limited Test Ban Treaties. A precedent for sharing some kinds of imagery with international bodies was established during the Gulf War and the UN enforcement of sanctions and demilitarisation against Iraq. Similarly, the United States has provided the IAEA with information on the North Korean programme. Additionally, proliferation has been elevated to an important place

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62. "Sun synchronous" orbits exploit the precession of the plane of the satellite orbit caused by the fact that the earth is not quite a sphere. If the right combination of orbital altitude and inclination is chosen, the orbit plane moves around the earth at just the rate to make the satellite view each spot on the equator at the same local solar time. Thus, the observations are said to be synchronised with the sun. Only a few practical combinations of altitude and inclination allow sun synchronicity. Both Spot and Landsat operate in sun synchronous orbits; radar satellites generally do not since solar illumination is irrelevant to their operation.

in the national security establishments of most nations; this is likely to induce those countries to make more resources available to combat proliferation. To the extent that deterring or detecting tests is perceived as a tool of non-proliferation or counter proliferation, one might expect national resources to be made available to an international organization under appropriate safeguards.

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