UTILIZATION OF GODDARD AND IITRI FORMULAE FOR THE EVALUATION OF THE COST OF SATELLITES

Application to the ESRO Programs

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1. Introduction and References

This memorandum has the goal of continuing work already undertaken at ESRO to apply the Goddard and IITRI for the purpose of estimating the cost of the ESRO satellite programs.

Two ESRO memoranda have already been published on this subject: [1] and [2].

In addition, these formulae have been used for estimating the cost of the LAS and the cosmic satellite. The two American references used are [3] and [4].

2. Presentation of the Goddard and IITRI Formulae

Before presenting the Goddard and IITRI formulae it is necessary that definitions of the cost of a satellite program be provided.

2.1 Total Cost of a Satellite Program

Let us first of all provide a definition of the total cost of an ESRO or NASA satellite program. This definition is perceptibly different from the one provided in [2] but it corresponds better to the definitions given in [3] and [4] and applied to ESRO for the LAS and COS projects. The total cost of the development of the C_p includes:

[1] Noordwijk, 27 June 1968, Department of Satellites and Sounding Rockets.

a) the cost of the development of the C_s satellite[1], including itself the development cost of the spacecraft C_{sc} and that of the development cost of scientific experiments C_E.

b) the support cost for mission C_{MS}; this cost including:

-the cost of supplementary ground support equipment for data acquisition.

-the cost of launch operations ar⁻ operations carried on during the service life of the satellite (data acquisition, communications, possible contractual support, etc...)

-the cost for analysis and data processing. The C_{MS} does not include ESRO or NASA personnel costs.

c) the cost of developing new testing installations and the location cost for existing test installations C_F.

d) the cost of the launch vehicle and the launch expenses for this vehicle C_L.

e) the cost of personnel (ESRO or NASA) participating in the program (project team, functional support, personnel indirectly involved) C_{MP}.

The following relation, hence, is true:

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[1] We shall use in this memorandum the terminology of the GSFC according to which a satellite is made up by a spacecraft and scientific experiments. This practical terminology has already been used for the LAS and COS. For communications satellites not including scientific experiments, only the term satellite will be employed.

$$C_P = C_S + C_{MS} + C_F + C_L + C_{MP}$$

with

$$C_S = C_{sc} + C_E$$

2.2 Presentation of the Goddard Formula

The model III Goddard formula is as follows:

$$C_S + C_{MS} = 148 \times CF^{1,24} \times (N \times W_T)^{1,08} \times (DTC \times TAR)^{0,035}$$

or

$C_S + C_{MS}$ is the development cost of the satellite and the support cost of the mission expressed as M.

CF is the complexity factor.

$$CF = \frac{W_{TD}}{W_T} \quad \text{with}$$

W_{TD} weight of the telecommunications and data processing system in pounds and W_T total weight of the satellite in pounds.

N is the total number of satellites in the program. The full prototype and the development models preceding it count for 1. Each flight model counts for 1.

DTC is the degree of compression of the development time. DTC includes four categories:

minimum DTC = 1

low DTC = 2

medium DTC = 3

high DTC = 4

TAR is the degree of technical advancement required for the program. TAR includes three categories:

low TAR = 1

medium TAR = 2

high TAR = 3

Indeed, as pointed out by [2], the product:

$$(DTC \times TAR)^{0,035}$$

is very close to 1 and hence can be disregarded. The linear approximation suggested in the same reference for the Goddard formula is completely valid.

$$C_S + C_{MS} = N \times WT \left(0{,}2 \frac{W_{TD}}{W_T} - 36 \times 10^{-4}\right).$$

In the continuation of this memorandum we shall use a formula G giving the cost in MFF for the weights in kg.

Formula G $$C_S + C_{MS} = N \times W_T \left(2{,}2 \frac{W_{TD}}{W_T} - 4 \times 10^{-2}\right).$$

The Goddard formula was set up beginning from the 12 following satellite programs:

-telecommunications satellites. A (Relay) - observatories B (OAO)

-telecommunications satellites. B - observatories D,

-satellit . for applications A - observatories A (OGO),

-meteorological satellites A - explorers C,

-meteorological satellites A' - explorers A

-observatories C (OSO) - explorers D.

The first part of Table No. 1 summarizes the results obtained by removing OAO whose cost is not known.

Comments

-The exponent C indicates that it is a matter of computed cost and exponent B that it concerns actual budgetary cost.

-The error is expressed by the Napier logarithm of the ratio of the cost computed with the budgetary cost.

$$\Delta = L\frac{C^C}{C^B} \quad \text{(a)}$$

This method for expressing the error is not useful when the errors are small but it is necessary when C^C is very different from C^B. Indeed, the conventional error formula:

$$\varepsilon = \frac{C^C - C^B}{C^B} \quad \text{(b)}$$

is no longer symmetrical and gives much more weight to errors of over estimation than to errors of under estimation. The (a) formula is symmetrical, this being much more logical, and it gives the same results as the (b) formula when Δ is low. The utilization of the (a) formula signifies that if $\Delta = 0.1$ the error is approximately 10%.

-the mean quadratic error is equal to 0.12 which corresponds to a ratio

$$\frac{C^C}{C^B} \quad \text{equal to 0.89 or 1.12.}$$

2.3 Presentation of the IITRI Formula

The definition of subsystems for the application of the IITRI formula requires some preliminary explanations. It is considered that the total dry weight of the W_{TS} satellite is made up of six parts:

W_S Weight of the structure subsystem including the structure in the true sense, devices for thermal control, pyrotechnic devices and the *wiring*.

W_{TD} Weight of the telecommunications and data processing subsystem including telemetry, command guidance, antennae, repeaters (in the case of telecommunications satellites), central computer, sequential devices, "housekeeping".

W_{PR} Dry weight of the propulsion subsystem including all the devices modifying the satellite path to the exclusion of the propellants.

W_{AC} Dry weight of the attitude control subsystem including all the devices measuring or controlling the attitude of the satellite around its center of gravity to the exclusion of the propellants.

W_{PS} Weight of the electrical power supply subsystem including the solar cells, batteries, governors, converters, etc...

W_E Weight of the subsystem including the scientific experiments. In the case of telecommunications satellite W_E it is generally zero.

Table No. 3 gives the value of the parameters W_{TS}, W_S, W_{TD}, W_{AC}, W_{PS} and W_E in kg and in percentage of the weight W_{TS} for different ESRO and NASA satellites..

The IITRI formula is then the following:

$$C_S = N \times \frac{W_{TS}}{W_{SC}} \{0,038 (W_{TD} + W_S) + 0,02 W_{PR}\}$$

where C_S is the satellite's development cost

N has the same definition as in the Goddard formula.

W_{TS} is the total dry weight of the satellite, i.e., the total weight W_T less the weight of the gas or propellants used in the propulsion and attitude control systems of the satellite. This weight is expressed in pounds.

W_{SC} is the spacecraft weight expressed in pounds.

W_{TD}, W_S and W_{PR} are the weights expressed in pounds of the systems for telecommunications, data processing, structure and propulsion.

We shall use in the following an IITRI formula providing the cost in MFF for weights in kg.

Formula I

$$C_S = N \times \frac{W_{TS}}{W_{SC}} \{0,42 (W_{TD} + W_S) + 0,25 W_{PR}\}$$

The IITRI formula was established beginning from the 10 following satellite programs:

- Ranger 1 - 5 -syncom
- Ranger 6 - 9 -OGO A-E

- Surveyor	1 - 7	-IMP	A-C
- Mariner	R	-IMP	D-E
- Mariner	64	-Relay	

The first part of Table No. 2 summarizes the results obtained by applying the formula to the above programs. The mean quadratic error is equal to 0.25 corresponding to a ratio

$$\frac{C^C}{C^B} \quad \text{equal to 0.77 or 1.28.}$$

This finding is not quite as good as in the preceding case of the Goddard formula.

3. Comparison of the Goddard and IITRI Formulae

It should first of all be noted that formulae G and I do not give the same cost. Formula G gives the cost for development support of the satellite C_S increased by the support cost for the mission C_{MS}, whereas the formula I gives only cost C_S. Apart from this, the two formulae are quite identical in form. The cost is proportional to the product N x W_T and with a complexity coefficient which in the case of formula G is based on the ratio $\frac{W_{TD}}{W_T}$ whereas formula I takes into account on an equal basis the structure subsystem and the propulsion subsystem.

It is interesting to note that these two formulae were not established beginning from the same programs. Only OGO and Relay programs are in common. It is, therefore, possible to apply each one of the formulae to the satellite programs selected to establish the other. The findings are shown in the second part of Tables No. 1 and No. 2.

The formula G applied to the IITRI gives a mean quadratic error of ± 0.635, whereas the formula I applied to the Goddard satellites gives an error of ± 0.455 which is clearly smaller. More especially, the formula G is applied very poorly (Δ = -1.5) to the Surveyor program arising from the fact that the ratio $\frac{W_{TD}}{W_T}$ for this satellite is small (0.07). This is likewise true for the IMP D-E program. (Δ = -0.830 for $\frac{W_{TD}}{W_T}$ = 0.08).

In the case of the application of formula I to the Goddard programs, a large overestimate appears for 2 programs: Δ = 0.875 for the program of application satellites A and Δ = 0.670 for the OSO program. Now, it was not possible to clearly identify the program of application satellites which makes the result of computation controversial. As for the OSO program, it is known to be a program which was rather inexpensive.

It can therefore be provisionally concluded, and this conclusion will be confirmed later on after application to the ESRO satellites, that the Goddard formula is only poorly applicable when programs are considered which were not used to establish it and especially when the ratio $\frac{W_{TD}}{W_T}$ is small.

4. Search for Improvement of the IITRI Formula-Formula I Modified

The IITRI document [4] explains how the formula was established. More particularly, the effect of each one of the subsystems on the final cost was studied and the three subsystems W_{TD}, W_S and W_{PR} appear as those having, in that order, the most effect. It is nevertheless surprising that a system as large and expensive as the attitude control does not become a factor in the formula. In the case of the TD 2 satellite, for example, the attitude control system alone accounts for more than 27% of the cost of the satellite. An attempt was therefore made to find a modified IITRI formula which would introduce the term W_{AC}. It was not possible to make a complete optimization for machine computations would be required which was not included within the scope of this memorandum. Nevertheless, the following formula appears advantageous:

Formula I Modified

$$C_S = N \frac{W_{TS}}{W_{SC}} \{ 0{,}36 \, (W_{TD} + W_S) + 0{,}25 \, (W_{PR} + W_{AC}) \}$$

This formula applied to the IITRI program gives a mean quadratic error of ± 0.24 or very slightly less than the one given by the original IITRI formula. In the case of the ESRO satellites, the IM formula gives more uniform results than the formula I. A more vigorous optimization would lead, undoubtedly, to better results.

5. Cost of Mission Support and Cost of Experimentation: Application of the IITRI and Modified IITRI Formulae to the ESRO Programs

The application of the G, I and IM formulae to the ESRO programs requires hypotheses on the cost of mission support compared to the cost of satellite development and on the cost of experiments compared to the cost of the satellite.

5.1 Cost of Mission Support

Table No. 4 provides, according to [3] and [4], the values of $C_S^B +$ $+ C_{MS}^B$ and C_{MS}^B in MFF for a certain number of NASA programs. In the fourth column of this table the ratio

$$\frac{C_{MS}^B}{C_S^B + C_{MS}^B}$$

is given in percentage. It can be seen that the dispersion of this percentage is quite large. On the average, it is possible to allow, nevertheless, a ratio of 10% except for the communications satellites for which this ratio is close to 50%.

5.2 Cost of Experiments

Table No. 4, likewise, provides the ratio in % of the cost of the experiments related to the cost of the satellites.

$$\frac{C_E^B}{C_S^B}.$$

This percentage is to be compared with the ratio in % of the weight of the experiments over the total weight of the satellite $\frac{W_E}{W_T}$. It can be seen that, for a given satellite, the values

$$\frac{C_E^B}{C_S^B}$$

and $\frac{W_E}{W_T}$ are quite close. It is possible therefore to accept the conclusion of [4] according to which *the cost in kg of the experiments of a satellite is, on the average, equal to the cost in kg of this satellite.*

5.3 Application to the ESRO Satellites

The application of the G, I and IM formulae to the ESRO satellites is provided by Table No. 5. The following hypotheses were made for establishing this table:

(a) The number N is identical for all satellites and equal to 3. Taking [3] and [4] into account, this hypothesis appears to be the most justified. It corresponds to a complete P2 prototype and with 2 flight units. In the case of TD2 it should be noted that the second flight unit is not integrated. The cost of this integration, moreover, would lead to an increase of 5MMF at the maximum.

(b) The reference cost considered C_S^B is the cost of the spacecraft alone. In the case of ESRO II, it is a matter of the actual cost up to launch of the first flight unit. In the case of ESRO I and HEOS, it is a matter of the best estimates that can be made at the present time, these estimates being close to the real cost. In the case of TD2, a single satellite was considered and added to this was the estimate of the agreed price given by the contractor on the basis of work packages (163 MFF) and the margin of risks foreseen by ESRO (25 MFF). In the case of the CETS, the estimate of the price made by ESRO was considered beginning from subsystems and a price estimate of the prime contractor was added.

(c) In order to obtain the cost of the spacecraft C_{SC}^C beginning from the cost $C_S^C + C_{MS}^C$ given by the Goddard formula, the conclusions of paragraphs 5.1 and 5.2 were accepted owing to the absence of data on the cost of mission support and on the experiments of the ESRO satellites. One exception to this rule was done for the LAS where the mission support cost was estimated in the PDP to approximately 20% of satellite cost.

(d) The conclusions of paragraph 5.2 have likewise been applied in order to obtain the cost of the spacecraft C^C_{SC} beginning from C^C_S provided by the formulae I and IM. It can be noted, in this respect, that these formulae can be written:

Formula I $$C_{SC} = N \{0,42 (W_{TD} + W_S) + 0,25 W_{PR}\}$$

Formula IM $$C_{SC} = N \{0,36 (W_{TD} + W_S) + 0,25 (W_{PR} + W_{AC})\}$$

5.4 Comments on Table No. 5

The values given in Table No. 5 are sometimes different from those that can be found in [1], [2] and in the LAS document. It is owing to the interpretation of the weight of the subsystems (paragraph 2.3) and to the fact that the IITRI formula includes the cost of scientific experiments contrary to what was applied for the LAS.

The Goddard formula provides very disperse and incoherent results for the HEOS, TD2 and CETS satellites. In these three cases, the underestimate provided by the formula is considerable. This is explained by the low value of the ratio $\frac{W_{TD}}{W_T}$ in the case of HEOS and TD2. This explanation was not adequate for CETS.

The modified IITRI and IITRI formulae provide rather close results. The results provided by the IM formula are, nevertheless, less disperse (included between + 0.30 and + 0.48 for the ESRO I, ESRO 2, HEOS and TD2 satellites instead of + 0.28 to 0.73 in the case of formula I). From the look of the results obtained for the four satellites mentioned above, it would appear that a certain transatlantic factor exists. This factor is probably on the order of about 1.35. Moreover, these results are not confirmed for CETS where Δ is negative. The explanation for CETS can only come from the fact that the formulae do not take into account the degree of technological complexity which is especially great for this satellite.

6. Conclusions

(a) The Goddard and IITRI formulae give a proportional cost to the number N, the latter being equal to the number of complete prototypes and to the number of flight units. For conventional ESRO projects, a number N = 3 is to be recommended even if the number of electric prototypes is not the same and even if the second flight unit is not integrated. Indeed, if the TD2 is considered, for example, the cost of one complete flight unit represents 10% of the total cost and not 33% as could be thought if the formula was applied to find this cost. *The number N = 3 therefore represents a convention.* In the NASA projects where N is large, it is a matter generally of series of satellites involving different experiments and occasionally requiring new prototypes (case of the Surveyor).

(b) The degree of technological complexity, not appearing in any of the formulae presented, should certainly be taken into account. The application to the CETS is an example of this. (The maximum degree of technological complexity considered in the Goddard formula before simplification is 3 which gives a negligible corrective factor of 1.04).

(c) The modified IITRI and IITRI formulae provide clearly better results than the Goddard formula both for the NASA programs as well as for the ESRO programs. The Goddard formula, giving too much importance to the single ratio $\frac{W_{TD}}{W_T}$, is not to be recommended.

(d) The modified IITRI formula appears to give less dispersed results than the IITRI formula, at least where the ESRO programs are concerned. The number of these programs is, nevertheless, too small for a definitive conclusion to be drawn.

(e) The IITRI formula or a derivative formula can be used just in order *to give an order of magnitude of the satellite cost.* The precision obtained can be estimated at approximately ± 30 or ± 40%.

It is clearly absolutely necessary to apply, from the very feasibility study stage, other methods of cost evaluation such as the evaluation of cost by subsystem.

(f) The Goddard and IITRI formulae are based on the cost of satellites whose production is staged generally between 1960 and 1965. For future ESRO projects, there are grounds for taking into account the increase in the cost of living.

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