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FLIGHT DYNAMICS LEOP AND ROUTINE OPERATIONS FOR SCD2, THE INPE'S SECOND ENVIRONMENTAL DATA COLLECTING SATELLITE

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The launch of the second INPE's environmental data collecting satellite, SCD2, is scheduled for May 1998, by the American Pegasus launcher. This satellite is similar to the SCD2-A, whose launch, in November 2, 1997, by the Brazilian VLS launcher unfortunately, failed. When compared with the SCD1, the SCD2 presents important differences concerned mainly to attitude stabilization and control. The paper presents, at first, an analysis of the main differences between the satellites and discusses their impacts on flight dynamics system and related operations. For instance, the restriction on spin-axis attitude is, for the SCD2, more stringent than the ones imposed on the SCD1, requiring the application of a Quarter-Orbit Magnetic Attitude Control procedure (QOMAC). The spin-axis attitude control of SCD2 is detailed and its performance is analyzed with help of available simulation results. Finally, the planning of the flight dynamics operations for the LEOP and routine phase of the SCD2 are discussed.

INTRODUCTION

The SCD1, the first environmental INPE's data relay satellite[1], completed five years into orbit on February 9th, 1998, still presenting an overwhelming overall performance. During the SCD1 mission exploitation, the Data Collecting Platforms (DCP) network, spread over the Brazilian territory, presented a significant increase, not only in quantity, but also in application diversity. During the first year after the launch, the network consisted of about 20 platforms[2]. Nowadays there are 204 operating DCPs, other 167 ones in acceptance phase and more 106 in acquisition process. As these figures show, the number of operating DCPs, which currently surpasses 10 times the initial ones, will soon be doubled. The existing DCPs comprise a great number of applications, mainly in the fields of Meteorology, Hydrology, Agricultural Planning, Geomagnetism, Atmospheric Chemistry, Tide Monitoring and Tropical Forest Regeneration studies.

In order to assure the continuity of the environmental data-collecting mission, the second data collecting satellite, the SCD2, has been scheduled by INPE to be placed in orbit on May 1998, by the North-American Pegasus launcher, which had successfully launched the SCD1[3-4] in February 1993. In spite of the existing similarities between SCD2 and SCD1, there are some differences that impose important changes on the ground attitude control system. The main differences and the consequences on the flight dynamics operations activities are exposed and discussed in the next section. A further section is dedicated to the presentation of the modified version[5] of a QOMAC[6] (Quarter Orbit Magnetic Attitude Control) algorithm for the spin-axis attitude control which will

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be used for the SCD2. The expected algorithm performance is discussed based upon simulation results. Finally, the main aspects of the flight dynamics operations for LEOP and routine phase planned for the SCD2 are presented. To close the paper a last section is dedicated to the presentation of the concluding remarks.

THE SCD2 SATELLITE

The SCD2 has been developed in order to assure continuity of Brazilian Data Environmental Data Collecting Mission, which is currently being performed using solely the SCD1 satellite. Like the SCD1, it will be spin stabilized and will be injected into a low altitude (≅750 km) orbit with 25º inclination. It will not have any orbit control. The attitude control subsystem is composed of a partially fluid filled nutation damper, a three-axis flux-gate type magnetometer, two redundant 180° field of view digital sun sensors, two redundant spin plane coil with magnetic moment of 4 Am^2 each, and one axis torque coil of 12 Am^2. The spin plane coil is automatically activated by an autonomous control system whenever the spin rate reaches the lower limit of its allowable variation range: 34 ± 2 rpm. The attitude sensors outputs will be sampled at a rate of 2 Hz. Regarding the axis coil, it will be activated by real-time or time-tagged telecommands in order to perform spin-axis attitude maneuvers. Time-tagged telecommands will be needed due to the use of the before mentioned QOMAC algorithm for spin-axis attitude control.

The SCD2 launch will be the INPE' second trial to put a new in-house manufactured data collecting satellite into orbit since the launch of SCD1. The first try was the launch of SCD2-A in the beginning of November 1997, from the Alcantara launching facility, in the north of Brazil. It has been the first shot of the Brazilian launcher VLS, which unfortunately failed due to a problem occurred in one of the first stage four boosters.

When compared to SCD1, the SCD2 presents some improvements, mainly related to attitude stabilization and control. The main differences between both satellites and their impacts on the flight dynamics ground operations are discussed in next sections.

SPIN-AXIS ATTITUDE

The SCD2 has the same shape as SCD1: octagonal prism with 0.7m height whose base fits within a circle of 1m diameter. The SCD1, however, has the whole lateral faces and the upper one covered by solar cells. The remaining bottom face is used as a heat sink by the passive thermal control subsystem. In this way, sunlight incidence on this face shall not occur, in order to avoid thermal problems with on-board equipment. As the spin-axis is the satellite longitudinal one, this restriction is equivalent to having $\theta \leq 90^\circ$ where θ is the sun aspect angle. In the case of the SCD2, only the lateral panels are covered by solar cells. However, the passive thermal subsystem of this satellite has been designed so as to allow direct sunlight incidence on the top and lower panels, with inclination up to 10°. In other words, for the SCD2, the sun aspect angle excursion is limited to the range: $80^\circ \leq \theta \leq 100^\circ$. In order to increase the time interval between the execution of successive spin-axis maneuvers, it has been decided to maintain the angle between the axis normal to the ecliptic plan and the spin-axis, ϕ, to less than 10º. It shall be noted that this condition necessarily implies in having $80^\circ \leq \theta \leq 100^\circ$. If spin-axis is aligned with the normal to ecliptic plan then the translation motion of the Earth around the Sun does not contribute for the sun aspect angle variation, resulting in a lower precession rate. As a consequence, the time needed by the angle ϕ to reach the control limit value becomes large, lowering the need of maneuver application. In this way, the target of the spin-axis attitude control for the SCD2 will be to maintain $\phi \leq 10^\circ$. Whenever the angle ϕ attains 10° a maneuver shall be executed in order to decrease this angle to less than 1°.

The operational range for spin-axis attitude excursion is narrower for the SCD2 than the one corresponding to SCD1. As a consequence, higher rate of maneuver executions will be required for the spin-axis attitude control of SCD2. Besides this, a more complex attitude control procedure will be needed in order to comply with the SCD2 spin-axis pointing requirement to be fitted after maneuver execution: $\phi \leq 1^\circ$. As mentioned earlier, a modified version of the QOMAC algorithm has been implemented for this purpose.

SPIN-AXIS ATTITUDE CONTROL PROCEDURE

As mentioned before, the ideal attitude for the SCD2 spin-axis is the direction orthogonal to the ecliptic plan. In the real case, however, it is allowed the variation up to 10° of the alignment error, ∅, between the satellite spin-axis and the ecliptic plan normal direction. In order to comply with this requirement, the strategy to be adopted will consist of monitoring the time evolution of ∅ with help of the attitude determination/propagation processes. When the ∅ predicted time evolution indicates that, in about two days, this angle value will overpasses its maximum allowable limit, then a decision to compute a spin-axis maneuver shall be taken. The goal of the attitude control procedure is to reduce the angular align error ∅ to the zero neighborhood. Actually, the final results of a spin-axis maneuver will be acceptable when ∅ is decreased to a value less than one degree.

In what follows boldfaced characters will represent vector variables and the same but not boldfaced characters will represent their magnitude. The x, y and z axes unit vectors of the satellite body-fixed coordinate system will be, respectively, denoted by **i**, **j** and **k**.

It is assumed that the satellite nutation motion is maintained near to zero by the action of the satellite partially fluid-filled nutation damper (cone angle less than 0.25°). As a consequence one can assume that the spin-axis is in the same direction of the satellite angular momentum, **L**, that is: $\mathbf{s} = \mathbf{k} \cong \mathbf{L}/L$, where **s** is the spin-axis unit vector. Calling **n** the unit vector of the direction orthogonal to the Ecliptic plan, the vector misalignment error between the spin-axis and **n** can be written as:

$$\mathbf{e} = \mathbf{n} - \mathbf{L}/L. \tag{1}$$

Hence,

$$e^2 = (\mathbf{n} - \mathbf{L}/L) \cdot (\mathbf{n} - \mathbf{L}/L) = 2(1 - \mathbf{n} \cdot \mathbf{L}/L). \tag{2}$$

In order to analyze the variation of the quadratic error as a function of the control torque, the derivative of Eq. 2 has been, at first, computed:

$$d(e^2)/dt = -2\mathbf{n} \cdot [(1/L)d\mathbf{L}/dt - (\mathbf{L} / L^2)dL/dt]. \tag{3}$$

The torque which arises from the interaction between the geomagnetic field, $\mathbf{B} = \mathbf{B_x}\,\mathbf{i} + \mathbf{B_y}\,\mathbf{j} + \mathbf{B_z}\,\mathbf{k}$, with the magnetic moment generated by the axis-coil, $\mathbf{M_{ac}}$, added to the z-axis component of residual one, $\mathbf{M_{re}}$, is given by:

$$\mathbf{T} = u.M.\mathbf{k} \times \mathbf{B} \tag{4}$$

$M = M_{ac} + M_{re}$, and u is the discrete control variable defined such as:

u = -1 if the axis-coil has been activated in inverse ($\mathbf{M_{ac}}$ in the -**k** direction),
u = 1 if the axis-coil has been activated in direct ($\mathbf{M_{ac}}$ in the **k** direction) and,
u = 0 if the axis-coil is deactivated ($M_{ac} = 0$).

As $M_{re} \ll M_{ac}$ then, when the axis-coil is activated, **M**, will have the same sense of $\mathbf{M_{ac}}$.

From Eq. 3 one can see that the torque **T** is always in the xy plane of the satellite reference frame and hence, orthogonal to the spin-axis direction. By this reason it will cause changes only in the spin-axis direction, having no effect on the spin-axis magnitude. As the magnitude variation of the satellite angular moment due to the effect of only environmental disturbing torque (mainly caused by eddy currents) is very slow then, during execution of spin-axis maneuver, one can assume that $dL/dt \cong 0$. Considering this assumption and recalling that $\mathbf{T} = d\mathbf{L}/dt$, the Eq. 3 can be put in the following form:

$$d(e^2)/dt = -(2/L)\mathbf{n} \cdot d\mathbf{L}/dt = -(2/L)\mathbf{n} \cdot \mathbf{T} \tag{5}$$

Applying the Eq. 4 in the equation above one finally arrives to:

$$d(e^2)/dt = -u(2M/L)v, \tag{6}$$

where $v = \mathbf{n} \cdot \mathbf{k} \times \mathbf{B}$.

Analyzing Eq. 6, one can conclude that the scalar v can be treated as a switching function. If v=0 then, in order to generate a control torque $u.M.\mathbf{k} \times \mathbf{B}$ which causes a reduction of the alignment error ($de/dt < 0$), one shall impose u=1. As seen above this means that the axis-coil polarity shall be commuted to the positive one. In the same way, Eq. 6, indicates that one shall impose the negative polarity to coil (u=-1) if v=-1, and deactivate the coil in the case of having v=0. This kind of spin-axis attitude control algorithm takes advantage of the fact that the local geomagnetic field on a satellite into an inclined orbit oscillates with a frequency of about the double of the orbital one. Hence, in order to generate the control torque in only one sense during the entire orbital period, four switching of the torque coil polarity are required. Due to this characteristic that this kind of algorithms is called QOMAC. The switching function, v, defines the adequate torque coil polarities and switching times needed to reduce the alignment error to the zero neighborhood.

In the routine phase of the SCD2 lifetime, the need of spin-axis maneuvers will be predicted by monitoring the alignment error with help of the attitude determination and propagation processes. Every time it is predicted that the spin-axis attitude will, after the next two days, overpass the maximum allowable limit of operation, then a new spin-axis maneuver shall be computed. The output of the maneuver calculation process consists of the control sequence $[(t_1, u_1), (t_2, u_2), ..., (t_m, u_m)]$ to be applied to the satellite in order to decrease the error near to zero ($\varnothing < 1°$, as seen before). The computed control sequence will be transmitted to the satellite in the form of time-tagged telecommands which are automatically executed by the on board computer in the proper time instants, t_i.

Results, which have been obtained from realistic simulations of a spin-axis maneuver execution for SCD2, covering a sixty day time interval, are presented in the Figure 1 and 2. Nominal parameter values were considered. The attitude integration step has been taken as 5 minutes. The Figure 1 shows the curve, which has been obtained for the alignment angle error, $\varnothing$, as a function of time. One can observe from this figure that three spin-axis maneuvers has been needed, during the considered simulation period, in order to maintain the alignment error inside the allowed variation range. Also observed is that the maneuver application rate is of about one maneuver each thirteen days, showing that, in nominal situation, no maneuver execution will be needed during LEOP.

Figure 1. Spin-axis Angle Alignment Error Time Evolution

The Figure 2 shows the time evolution of the discrete control variable, u, during the first maneuver execution time.

Figure 2. Coil Polarity During Maneuver Executing Time

SPIN RATE

The SCD1 has no spin rate control. It has been launched with spin rate of 120 rpm, which decayed to current values of about 50 rpm. In order to reduce the time required for execution of spin-axis maneuver, the spin rate has been reduced for SCD2 to the rage between 32 to 36 rpm. Every time the spin rate decreases to the lower limit an autonomous control system driven by magnetometer outputs automatically activates the spin plane torque coils, in order to increase again the spin rate up to the maximum value (36-rpm). If, on one hand, having a lower spin rate will reduce the time needed to perform spin-axis attitude maneuvers, on the other hand it will reduce the time between two successive maneuvers, since the precession motion will also be faster.

Calling $\mathbf{B_{xy}}$ the orthogonal projection of the geomagnetic field in the satellite frame xy-plane and $\mathbf{M_{pc}}$ to the magnetic moment of a magnetic coil fixed along the x-direction, the torque generate by the interaction between $\mathbf{M_{pc}}$ and the geomagnetic field, $\mathbf{T_{pc}}$, is then given by:

$$\mathbf{T_{pc}} = u_{pc}\, \mathbf{M_{pc}} \times \mathbf{B_{xy}} = u_{pc}\, M_{pc}\, B_{xy} \sin\beta\, \mathbf{k}. \qquad (7)$$

In this equation: u_{pc} is the discrete spin rate control variable which defines the plane coil state: deactivated ($u_{pc} = 0$), activated in the direct sense ($u_{pc} = 1$) or in the inverse sense ($u_{pc} = -1$) and β is the phase angle between the plane coil axis and B_{xy}. As the coil is aligned with the x-axis of the satellite frame one can write:

$$B_{xy}\sin\beta = B_y. \qquad (8)$$

Hence, the Eq. 7 becomes:

$$\mathbf{T_{pc}} = u_p .\, M_{pc}\, B_y\, \mathbf{k}. \qquad (9)$$

This equation shows that, the control variable u_p shall have the same or opposite sign of B_y in order to , respectively, increase or decrease the satellite spin. In this way, as B_y has a sinusoidal time variation at satellite rotation frequency, in order to control the spin rate the plane coil polarity shall be commuted every half rotation. In the case of SCD2 this is accomplished automatically with help of the y-axis output signal of the satellite three-axis magnetometer. During actuating periods of the spin rate control system, the plane coil polarity is automatically commuted every time the magnetometer output voltage changes signal. As mentioned above, the control system will be automatically activated every time the satellite rotation decreases to 32 rpm. When, under its action the spin rate is increased to 36 rpm the system actuation stops. The spin rate, then, begins to decrease again under the main influence of the z-axis component of the eddy current torque. Calling ω to the satellite angular velocity magnitude and p to the eddy-current parameter, which depends on the satellite geometry and material conductivity, this torque is given by:

$$\mathbf{T_{ed}} = -p\omega\, (B_y^2 + B_y^2)\mathbf{k}. \qquad (10)$$

Is important to mention that, as a redundant way, the spin-axis control system can also be activated from the ground by telecommands.

The SCD2 will be inserted into orbit with a spin rate of about 50rpm. Although this rate is greater than the nominal upper limit value (36rpm), the activation from the ground of the spin rate control system, in order to reduce the rotation, is not intended to be performed. The spin rate control shall automatically actuate the first time only when the rotation naturally underpasses the down limit of the operation range (32 rpm). During the satellite in-orbit acceptance tests, however, the system performance will be analyzed.

DIFERENCE ON SCD2 ANTENNAS POLARIZATION AND CONSEQUENCES

The SCD1 has TM/TC and payload antennas on both its top and lower panels. All satellite antennas work in LHC (Left-Hand Circular) polarization. The SCD2 has also TM/TC antennas on both panels but it has only one payload antenna located on the lower panel. Another important difference between the satellites concerning to its antennas is related to the antenna polarization. In the SCD2 case the antennas of the top and lower panel work in opposite polarization.

It has been observed in the SCD1 that the use of same polarization for both the upper and lower panel antennas caused a small satellite to ground communications silent periods, when the angle between the ground station to satellite and spin-axis directions (aspect angle) is near 90 degree. Actually, these silent periods showed to be very weak being not enough to cause the loss of the down and uplinks. During its occurrences the down link signal becomes a little noisy, returning, however, to the normal state after few seconds. The silent periods are predicted with help of the attitude determination process and inserted in the pass prediction reports, which are periodically sent to the ground stations. The actions of sending telecommands or performing ranging sections are avoided during the time intervals when silent zones are predicted to happen. In the case of SCD2, the occurrence of satellite to ground silent periods are expected to be eliminated by the use of opposite polarization between the top and bottom panel antennas. The existence of such periods will, however, be replaced by the need of commuting the ground station antenna polarization each time the aspect angle passes through 90 degrees. With this purpose the ground stations antenna control software has been modified in order to read from the pass prediction file, the information about the instant when the aspect angle cross 90 degrees during a given pass, and automatically to commute, in real time, the antenna polarization. This feature makes invisible to ground station operator the occurrence of ground antenna polarization commutations, at least concerning to the downlink signal. The TM reception is not interrupted when such commutations occur. Unfortunately, that is not the case with the uplink signal. The uplink is always lost when the satellite antenna which is receiving the ground station signal, is replaced by the other one located at the opposite panel, due to the evolution of the satellite to ground station relative attitude. About 30 seconds is needed to reestablish the uplink, each time it is lost. This is a great disadvantage of being adopted different polarization between the top and lower panel antennas.

LEOP AND ROUTINE PLANNING OF FLIGHT DYNAMICS OPERATIONS

The Figure 3 shows the first nominal orbit ground tracks of the SCD2, and the visibility regions of the Alcântara and Cuiabá ground stations antennas. It is to be noted that the two first orbits are visible only from Alcântara. The first sequence of eight orbits, which are visible from Cuiabá, only begins on the third one.

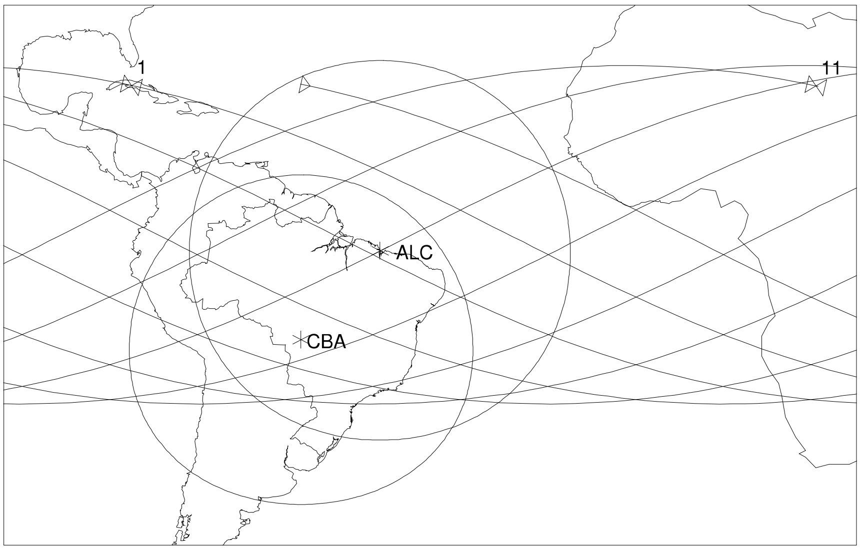

Figure 3. First Orbit Ground Tracks

The needed information about the injection time and related orbit and attitude state, are expected to be furnished to INPE by the Launcher Control Center in up to half hour since the in-orbit injection. The received data set will be analyzed and compared with the nominal one. At first it will be validated, in order to verify if it not presents incoherently large errors, which could be caused by problems occurred in any phase of the data acquisition and transmission process. In the case the validation shows there have been a problem with the data, and if a new set of valid data could not be available before the next pass over Alcântara then, the next pass will be predicted from the nominal orbit and attitude state at injection point. In the other case, the ground station pass prediction data will be computed by using the just received information as initial conditions. Redundant pass prediction set, redundantly computed from nominal parameters, will be employed, if the use of the previous set do not results in a ready satellite signal acquisition from the ground station antenna.

From here it will be described the planned flight dynamics operations during the considering the nominal situation. Independently of which initial information set has been used in the generation of the first pass prediction data, it is assumed that, in the future passes, the satellite signal is acquired with no problem by both ground stations.

After the second satellite pass over Alcântara the first orbit determination is planned to be performed. The obtained results will be used in the generation of the pass prediction data set for tracking the third orbit. Redundant set of pass prediction will also be computed from the initial conditions used to track the previous pass.

In the third orbit, as seen before, the satellite begins a sequence of eight consecutive passes over Cuiabá. One orbit determination after each pass is planned to be performed until the end of the first cycle of visible passes over Cuiabá. Each one of them will be generated from the entire set of ranging date generated until the corresponding running time. At the end of the first cycle of passes over Cuiabá, the orbit determination results will, nominally, be accurate enough in order to allow the generation of one-day pass prediction data set. In this way, after the eighth orbit only one orbit determination will be performed each day. After the first week since orbit injection, a weekly routine will be adopted. At this time, in the nominal situation, the accuracy of the pass prediction will be good enough, in order allows the satellite tracking during the next three weeks, with no satellite signal acquisition problem. From this time a weekly routine will then be adopted for orbit determination.

The SCD2 attitude determination process is similar to the SCD1 one[7]. It is needed not only in order to monitor and control the spin-axis attitude. For this satellite also needed is to compute, and include in the pass predictions, the information concerning the instant when the aspect angle will cross 90 degrees, during each predicted pass. When this occur, as explained in a previous section, the ground station antenna polarization shall be readily commuted. In the initial orbits, one **preliminary attitude determination** is expected to be performed after each satellite pass over the ground stations. The preliminary attitude determination process, consists of the estimation of the satellite angular velocity vector, $\boldsymbol{\omega}$, from the entire amount of the telemetry data which has been collected during one satellite pass. In this way, after each pass, by the execution of the preliminary attitude determination process an updated estimation of $\boldsymbol{\omega}$ will be obtained from the attitude data which has been generated in the just finished pass. This estimate will be used, together with the orbit determination results, in the computation of the next pass prediction set to be sent to the ground stations. The first **fine attitude determination** will be performed only one week after the injection. This process consists of the computation of an improved estimate of $\boldsymbol{\omega}$, added to the estimates of M_{re},(residual magnetic moment) and p (eddy current parameter) by using as observation the estimates of the satellite angular velocity which has been computed by the previous preliminary attitude determination. The estimates of M_{re} and p are used in the attitude propagation process in order to improve its accuracy. After the execution of the first fine attitude determination the both this process and the preliminary one will follows a weekly execution routine.

Once the Pegasus launcher has maneuver capability, which allows the insertion of the satellite in the required attitude then, in the nominal case, no spin-axis maneuver execution will be needed during LEOP. The first spin-axis attitude maneuver is, as mentioned before, foreseen to be applied only when the lower limit of the alignment angle, $\varnothing$, will be, by the first time, attained, during the routine phase.

CONCLUSIONS

The SCD2 shows some important differences when compared with SCD1. These differences mainly imposed more stringent restrictions to the satellite attitude control. In order to satisfy the new spin-axis attitude alignment accuracy, a new software needed to be developed, in order to implement a more sophisticated attitude control algorithm. Besides, the significant reduction of the spin-axis attitude variation range imposed the need of having a greater rate of maneuver application for the SCD2. In order to reduce the gyroscopic resistance to spin-axis attitude changes, and in this way to reduce the maneuver duration, a lower nominal spin-rate value of about 32 ± 2 rpm has been adopted. In order to avoid that the spin rate can decrease to excessively small values, which can imply losing the satellite attitude stabilization, an autonomous spin-rate control system has been added to the satellite equipment.

The SCD2 operation will add to INPE flight dynamics crew an important gain of experience on the subject of the economic and functional magnetic attitude control of spin stabilized satellites.

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